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Solar-energy drying systems: A review

Atul Sharma *, C.R. Chen, Nguyen Vu Lan

Department of Mechanical Engineering, Kun Shan University, 949, Da-Wan Road, Yung-Kang City, Tainan Hsien 71003, Taiwan, ROC

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ABSTRACT

In many countries of the world, the use of solar thermal systems in the agricultural area to conserve vegetables, fruits, coffee and other crops has shown to be practical, economical and the responsible approach environmentally. Solar heating systems to dry food and other crops can improve the quality of the product, while reducing wasted produce and traditional fuels—thus improving the quality of life, however the availability of good information is lacking in many of the countries where solar food processing systems are most needed. Solar food dryers are available in a range of size and design and are used for drying various food products. It is found that various types of driers are available to suit the needs of farmers. Therefore, selection of dryers for a particular application is largely a decision based on what is available and the types of dryers currently used widely. A comprehensive review of the various designs, details of construction and operational principles of the wide variety of practically realized designs of solar-energy drying systems reported previously is presented. A systematic approach for the classification of solar-energy dryers has been evolved. Two generic groups of solar-energy dryers can be identified, viz. passive or natural-circulation solar-energy dryers and active or forced-convection solar-energy dryers. Some very recent developments in solar drying technology are highlighted.

Contents

1. Introduction

Drying using the sun under the open sky for preserving food and agricultural crops has been practiced since ancient times. However, this process has many disadvantages: spoilt products due to rain, wind, moisture and dust; loss of produce due to birds and animals; deterioration in the harvested crops due to decomposition, insect attacks and fungi, etc. Further, the process is labor intensive, time consuming and requires a large area for spreading the produce out to dry. Artificial mechanical drying, a relatively recent development, is energy intensive and expensive, and ultimately increases the product cost.

Solar-drying technology offers an alternative which can process the vegetables and fruits in clean, hygienic and sanitary conditions

* Corresponding author.
E-mail address: atul_sharma2@yahoo.com (A. Sharma).

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to national and international standards with zero energy costs. It saves energy, time, occupies less area, improves product quality, makes the process more efficient and protects the environment. Solar drying can be used for the complete drying process or as a supplement to artificial drying systems, in the latter case reducing the fuel energy required. Solar dryer technology can be used in small-scale food processing industries to produce hygienic, good quality food products. At the same time, this can be used to promote renewable energy sources as an income-generating option. Further, this solar technology is ideally suited for women since they can place a load in the dryer and then get on with their other numerous tasks.

Many of the third world countries produce large quantities of fruits and vegetables for local consumption and export. According to the Food and Agricultural Organization [1] the estimates for 1990 were approximately 341.9 million metric tons. In Asia, India produces 27.8 million metric tons or 8.1%, while China has a production capacity of 21.5 million metric tons or 6.3% of the total world production. Many of these fruits and vegetables contain a large quantity of initial moisture content and are therefore highly susceptible to rapid quality degradation, even to the extent of spoilage, if not kept in thermally controlled storage facilities. Therefore, it is imperative that, besides employing reliable storage systems, post-harvest methods such as drying can be implemented hand-in-hand to convert these perishable products into more stabilized products that can be kept under a minimal controlled environment for an extended period of time.

Many food industries dealing with commercial products employ state-of-the-art drying equipment such as freeze dryers, spray dryers, drum dryers and steam dryers. The prices of such dryers are significantly high and only commercial companies generating substantial revenues can afford them. Therefore, because of the high initial capital costs, most of the small-scale companies dealing directly with farmers are not able to afford the price of employing such high-end drying technologies that are known to produce high quality products. Instead cheaper, easy-to-use and practical drying systems become appealing to such companies or even to the rural farmers themselves. It is also useful to note that in many remote-farming areas in Asia, a large quantity of natural building material and bio-fuel such as wood are abundant but literacy in science and technology is limited.

Agricultural and other products have been dried by the sun and wind in the open air for thousands of years. The purpose is either to preserve them for later use, as is the case with food; or as an integral part of the production process, as with timber, tobacco and laundering. In industrialized regions and sectors, open air drying has now been largely replaced by mechanized driers, with boilers to heat incoming air, and fans to force it through at a high rate. Mechanized drying is faster than open-air drying, uses much less land and usually gives a better quality product. But the equipment is expensive and requires substantial quantities of fuel or electricity to operate. 'Solar drying' in the context of this technical brief, refers to methods of using the sun's energy for drying, but *excludes* open air sun drying. The justification for solar driers is that they may be more effective than sun drying, but have lower operating costs than mechanized driers. A number of designs are proven technically and while none are yet in widespread use, there is still optimism about their potential.

Solar drying is a potential decentralized thermal application of solar energy particularly in developing countries [2–5]. However, so far, there has been very little field penetration of solar drying technology. In the initial phase of dissemination, identification of suitable niche areas for using solar dryers would be extremely helpful towards their market penetration. In this context, one of the possible areas of immediate intervention in developing countries appears to be the solar drying of cash crops such as tobacco, tea, coffee, grapes raisin, small cardamom, chilli, coriander seeds, ginger, turmeric, black pepper, onion flakes, and garlic flakes, etc. For such crops, even with the capital-intensive nature of solar dryers, the unit cost of solar drying is expected to be a small fraction of the selling price of the dried product. In this paper, an attempt has been made towards potential assessment of solar drying of some cash crops in India. The resulting net mitigation of CO_2 emissions due to realization of the estimated potential of solar drying of the selected cash crops has also been estimated.

Solar drying is often differentiated from "sun drying" by the use of equipment to collect the sun's radiation in order to harness the radiative energy for drying applications. Sun drying is a common farming and agricultural process in many countries, particularly where the outdoor temperature reaches 30 °C or higher. In many parts of South East Asia, spice crops and herbs are routinely dried. However, weather conditions often preclude the use of sun drying because of spoilage due to rehydration during unexpected rainy days. Furthermore, any direct exposure to the sun during high temperature days might cause case hardening, where a hard shell develops on the outside of the agricultural products, trapping moisture inside. Therefore, the employment of solar dryer taps on the freely available sun energy while ensuring good product quality via judicious control of the radiative heat. Solar energy has been used throughout the world to dry food products. Such is the diversity of solar dryers that commonly solar-dried products include grains, fruits, meat, vegetables and fish. A typical solar food dryer improves upon the traditional open-air sun system in five important ways:

(1) It is faster. Foods can be dried in a shorter period of time. Solar food dryers enhance drying times in two ways. Firstly, the translucent, or transparent, glazing over the collection area traps heat inside the dryer, raising the temperature of the air. Secondly, the flexibility of enlarging the solar collection area allows for greater collection of the sun's energy.
(2) It is more efficient. Since foodstuffs can be dried more quickly, less will be lost to spoilage immediately after harvest. This is especially true of products that require immediate drying such as freshly harvested grain with high moisture content. In this way, a larger percentage of food will be available for human consumption. Also, less of the harvest will be lost to marauding animals and insects since the food products are in safely enclosed compartments.
(3) It is hygienic. Since foodstuffs are dried in a controlled environment, they are less likely to be contaminated by pests, and can be stored with less likelihood of the growth of toxic fungi.
(4) It is healthier. Drying foods at optimum temperatures and in a shorter amount of time enables them to retain more of their nutritional value such as vitamin C. An added bonus is that foods will look and taste better, which enhances their marketability and hence provides better financial returns for the farmers.
(5) It is cheap. Using freely available solar energy instead of conventional fuels to dry products, or using a cheap supplementary supply of solar heat, so reducing conventional fuel demand can result in significant cost savings.

Drying help in reducing the moisture content to a level below which deterioration does not occur and the product can be stored for a definite period. Different crops have different level of safe moisture content as given in Table 1 [6–8].

Table 1
Initial and final moisture content and maximum allowable temperature for drying for some crops [6,7].

S. no	Crop	Initial moisture content (%, w.b.)	Final moisture content (%, w.b.)	Max. allowable temp. (°C)
1	Paddy, raw	22–24	11	50
2	Paddy, parboiled	30–35	13	50
3	Maize	35	15	60
4	Wheat	20	16	45
5	Corn	24	14	50
6	Rice	24	11	50
7	Pulses	20–22	9–10	40–60
8	Oil seed	20–25	7–9	40–60
9	Green peas	80	5	65
10	Cauliflower	80	6	65
11	Carrots	70	5	75
12	Green beans	70	5	75
13	Onions	80	4	55
14	Gralic	80	4	55
15	Cabbage	80	4	55
16	Sweet potato	75	7	75
17	Potatoes	75	13	75
18	Chillies	80	5	65
19	Apples	80	24	70
20	Apricot	85	18	65
21	Grapes	80	15–20	70
22	Bananas	80	15	70
23	Guavas	80	7	65
24	Okra	80	20	65
25	Pineapple	80	10	65
26	Tomatoes	96	10	60
27	Brinjal	95	6	60

2. Working principle

Solar dryers can broadly be categorized into direct, indirect and specialized solar dryers [9]. Direct solar dryers have the material to be dried placed in an enclosure, with a transparent cover on it. Heat is generated by absorption of solar radiation on the product itself as well as on the internal surfaces of the drying chamber. In indirect solar dryers, solar radiation is not directly incident on the material to be dried. Air is heated in a solar collector and then ducted to the drying chamber to dry the product [10]. Specialized dryers are normally designed with a specific product in mind and may include hybrid systems where other forms of energy are also used [11–13]. Although indirect dryers are less compact when compared to direct solar dryers, they are generally more efficient. Hybrid solar systems allow for faster rate of drying by using other sources of heat energy to supplement solar heat.

The three modes of drying are: (i) open sun, (ii) direct and (iii) indirect in the presence of solar energy. The working principle of these modes mainly depends upon the method of solar-energy collection and its conversion to useful thermal energy.

2.1. Open sun drying (OSD)

Fig. 1 shows the working principle of open sun drying by using solar energy. The short wavelength solar energy falls on the uneven crop surface. A part of this energy is reflected back and the remaining part is absorbed by the surface depending upon the colour of crops. The absorbed radiation is converted into thermal energy and the temperature of crop stars increasing. This result in long wavelength radiation loss from the surface of crop to ambient air through moist air. In addition to long wavelength radiation loss there is convective heat loss too due to the blowing wind through moist air over the crop surface. Evaporation of moisture takes place in the form of evaporative losses and so the crop is dried. Further a part of absorbed thermal energy is conducted into the interior of

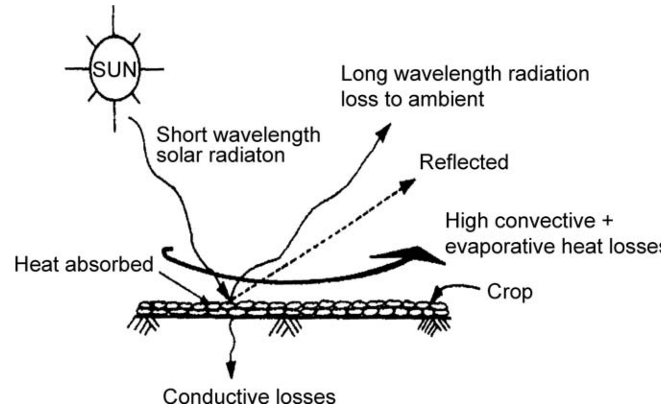


Fig. 1. Working principle of open sun drying.

the product. This causes a rise in temperature and formation of water vapor inside the crop and then diffuses towards the surface of the crop and finally losses thermal energy in the crop and then diffuses towards the surface of the crop and finally losses the thermal energy in the form of evaporation. In the initial stages, the moisture removal is rapid since the excess moisture on the surface of the product presents a wet surface to the drying air. Subsequently, drying depends upon the rate at which the moisture within the product moves to the surface by a diffusion process depending upon the type of the product [14].

In open sun drying, there is a considerable loss due to various reasons such as rodents, birds, insects and micro-organisms. The unexpected rain or storm further worsens the situation. Further, over drying, insufficient drying, contamination by foreign material like dust dirt, insects, and micro-organism as well discolouring by UV radiation are characteristic for open sun drying. In general, open sun drying does not fulfill the international quality standards and therefore it cannot be sold in the international market.

With the awareness of inadequacies involved in open sun drying, a more scientific method of solar-energy utilization for crop drying has emerged termed as controlled drying or solar drying.

2.2. Direct solar drying (DSD)

The principle of direct solar crop drying is shown in Fig. 2. This is also called cabinet dryer. A part of incidence solar radiation on the glass cover is reflected back to atmosphere and remaining is transmitted inside cabin dryer. Further, a part of transmitted radiation is reflected back from the surface of the crop. The remaining part is absorbed by the surface of the crop. Due to the absorption of solar radiation, crop temperature increase and the crop starts emitting long wavelength radiation which is not allowed to escape to atmosphere due to presence of glass cover unlike open sun drying. Thus the temperature above the crop inside chamber becomes higher. The glass cover server one more purpose of reducing direct convective losses to the ambient which further become beneficial for rise in crop and chamber temperature respectively. However, convective and evaporative losses occur inside the chamber from the heated crop. The moisture is taken away by the air entering into the chamber from below and escaping through another opening provide at the top as shown in Fig. 2.

A cabinet dryer has the following limitation:

(a) Due to its small capacity its use is limited to small scale applications.
(b) Discolouration of crop due to direct exposure to solar radiation.
(c) Moisture condensation inside glass covers reducing its transmittivity.

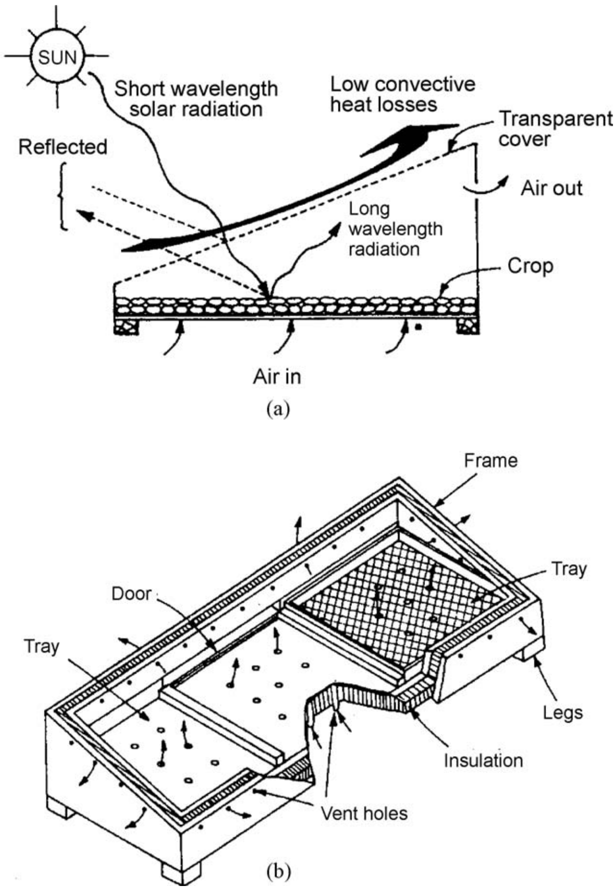


Fig. 2. Working principle of direct solar drying.

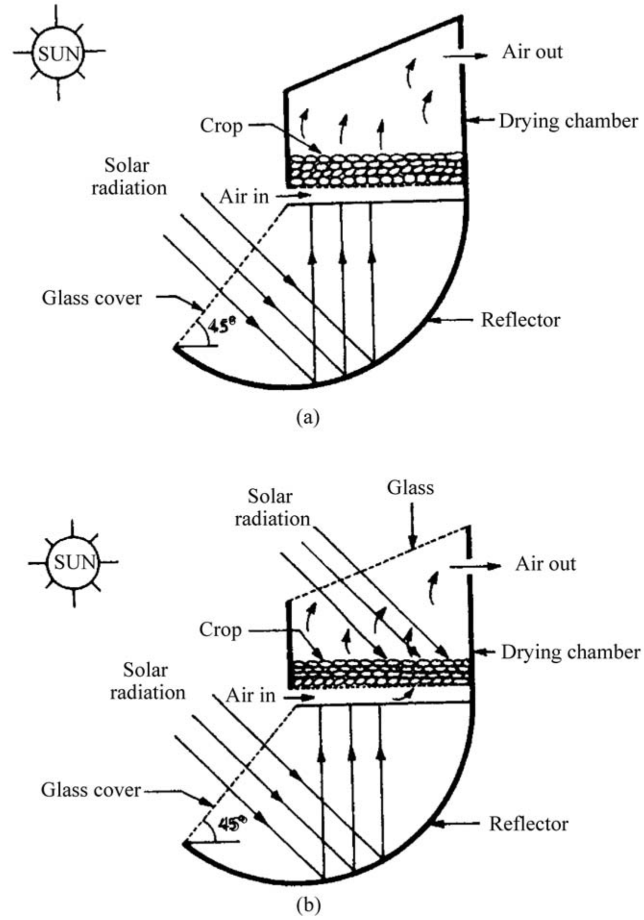


Fig. 3. Schematic view of single tray reverse absorber cabinet dryer: (a) without glass and (b) with glass.

(d) Sometimes the insufficient rise in crop temperature affecting moisture removes.
(e) Limited use of selective coatings on the absorber plate.

2.3. Indirect solar drying (ISD)

The crop is not directly exposed to solar radiation to minimize discolouration and cracking on the surface of the crop. Goyal and Tiwari [15] have proposed and analyzed reverse absorber cabinet dryer (RACD). The schematic view of RACD without and with glass is shown in Fig. 3. The drying chamber is used for keeping the crop in wire mesh tray. A downward facing absorber is fixed below the drying chamber at a sufficient distance from the bottom of the drying chamber. A cylindrical reflector is placed under the absorber fitted with the glass cover on its aperture to minimize convective heat losses from the absorber. The absorber can be selectively coated. The inclination of the glass cover is taken as 45° from horizontal to receive maximum radiation. The area of absorber and glass cover are taken equal to the area of bottom of drying chamber. Solar radiation after passing through the glass cover is reflected by cylindrical reflector toward a absorber. After absorber, a part of this is lost to ambient through a glass cover and remaining is transferred to the flowing air above it by convection. The flowing air is thus heated and passes through the crop placed in the drying chamber. The crop is heated and moisture is removed through a vent provided at the top of drying chamber.

Fig. 4 describes another principle of indirect solar drying which is generally known as conventional dryer. In this case, a separate unit termed as solar air heater is used for solar-energy collection for heating of entering air into this unit. The air heater is connected to a separate drying chamber where the crop is kept. The heated air is allowed to flow through wet crop. Here, the heat from moisture evaporation is provided by convective heat transfer between the hot air and the wet crop. The drying is basically by the difference in moisture concentration between the drying air and the air in the vicinity of crop surface. A better control over drying is achieved in indirect type of solar drying systems and the product obtained is good quality.

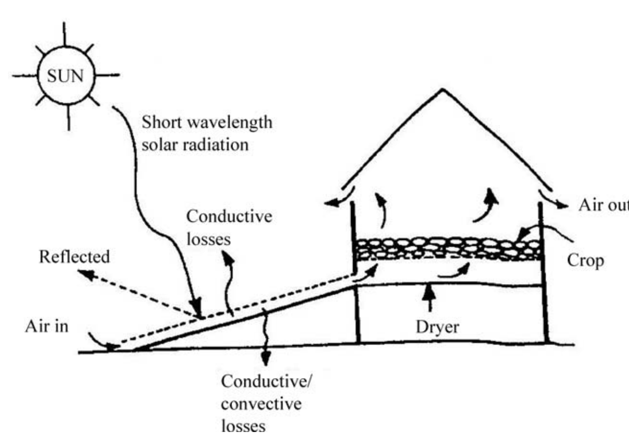


Fig. 4. Working principle of indirect solar drying system.

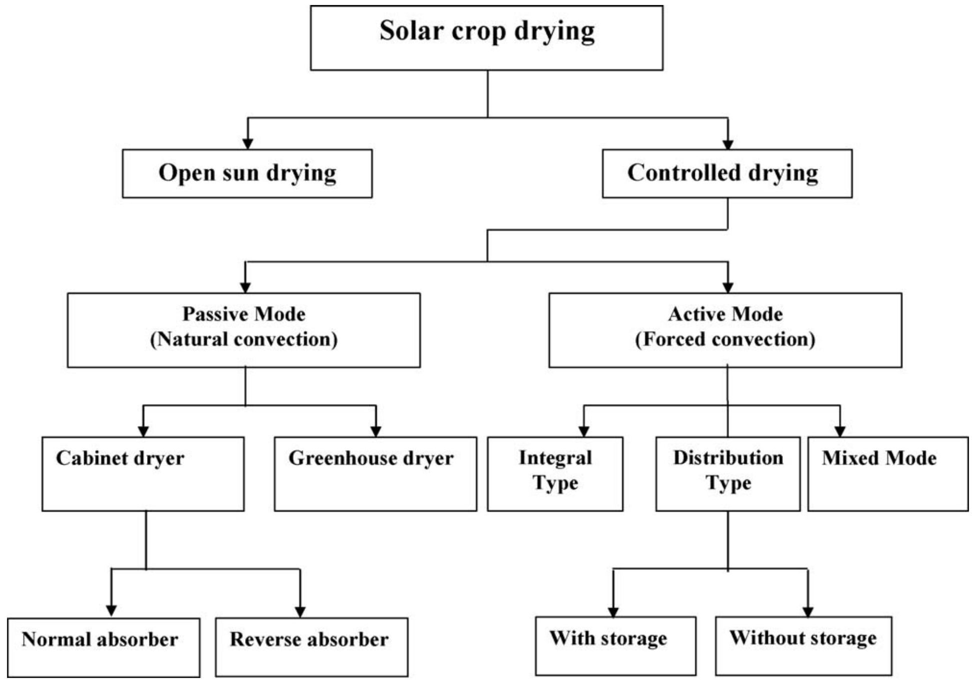


Fig. 5. Classification of crop drying using solar energy.

In a passive solar dryer, air is heated and circulated naturally by buoyancy force or as a result of wind pressure or in combination of both. Normal and reverse absorber cabinet dryer and greenhouse dryer operates in passive mode. The active solar dryers solar energy and motorized and fans/pumps for air circulation. All active solar dryer are, thus, by their application, forced convection dryer. In a integral type active dryers, the solar collector forms an integral part of the roof/wall of the drying/storage chamber. A distributed type active solar dryer is one in which the solar collector and drying chamber are separate units. Mixed-mode type dryer are rather uncommon designs and it combines some features of the integral and distributed type.

3. Types of solar dryer

Solar dryers can generally be classified into two broad categories: active and passive (Fig. 5). Passive dryers use only the natural movement of heated air. They can be constructed easily with inexpensive, locally available materials which make them appropriate for small farms where raw construction material such as wood is readily available.

A direct passive dryer is one in which the food is directly exposed to the sun's rays. Direct passive dryers are best for drying small batches of fruits and vegetables such as banana, pineapple, mango, potato, carrots and French beans [16]. This type of dryer comprises of a drying chamber that is covered by a transparent cover made of glass or plastic. The drying chamber is usually a shallow, insulated box with air-holes in it to allow air to enter and exit the box. The food samples are placed on a perforated tray that allows the air to flow through it and the food. Fig. 6 shows a schematic of a simple direct dryer [17]. Solar radiation passes through the transparent cover and is converted to low-grade heat when it strikes an opaque wall. This low-grade heat is then trapped inside the box by what is known as the "greenhouse effect." Simply stated, the short wavelength solar radiation can penetrate the transparent cover. Once converted to low-grade heat, the energy radiates as a long wavelength that cannot pass back through the cover.

Active solar dryers are designed incorporating external means, like fans or pumps, for moving the solar energy in the form of heated air from the collector area to the drying beds. Fig. 7 shows a schematic of the major components of an active solar food dryer. The collectors should be positioned at an appropriate angle to optimize solar-energy collection. A gear system can be designed to annually adjust the angle of the collectors. Tilting the collectors is more effective than placing them horizontally, for two reasons. Firstly, more solar energy can be collected when the collector surface is nearly perpendicular to the sun's rays. Secondly, by tilting the collectors, the warmer, less dense air rises naturally into the drying chamber. In an active dryer, the solar-heated air flows through the solar drying chamber in such a manner as to contact as much surface area of the food as possible. Thinly sliced foods are placed on drying racks, or trays, made of a screen or other material that allows drying air to flow to all sides of the food. Once inside the drying chamber, the warmed air will flow up through the stacked

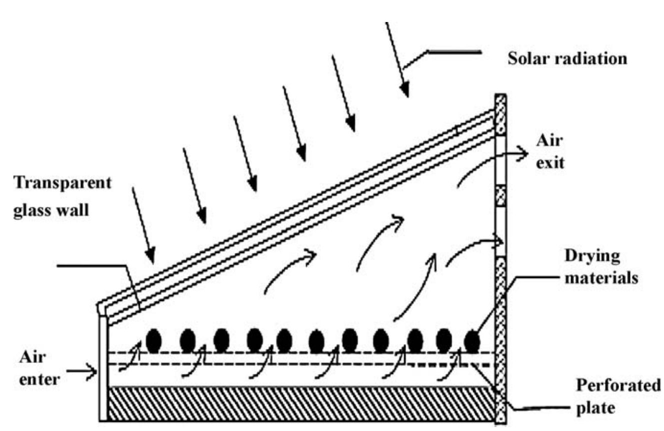


Fig. 6. Structure of a passive cabinet food solar dryer.

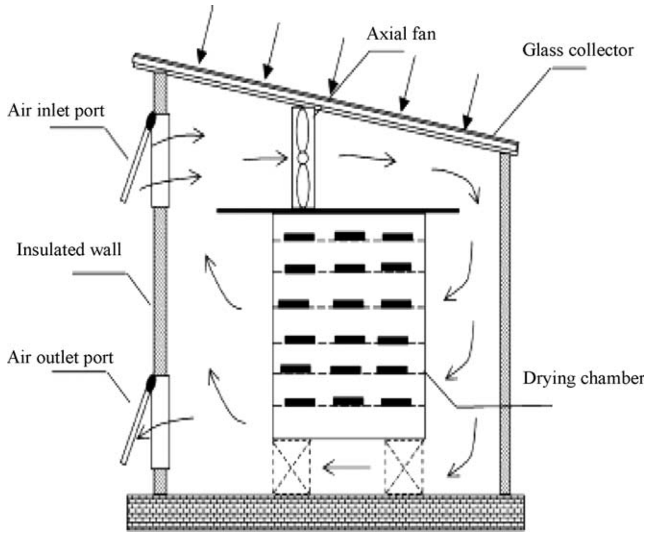


Fig. 7. Structure of an active solar convective dryer.

food trays. The drying trays must fit snugly into the chamber so that the drying air is forced through the mesh and food [18]. Trays that do not fit properly will create gaps around the edges, causing large volumes of warm air to bypass the food, and prevent the dryer from maximizing the potential of the drying air to remove moisture from the food. As the warm air flows through several layers of food on trays, it becomes moisture laden. This moist air is vented out through the outlet port. Fresh air is then taken in to replace the exhaust air. Active solar dryers are known to be suitable for drying higher moisture content foodstuffs such as papaya, kiwi fruits, brinjal, cabbage and cauliflower slices.

4. Solar-energy drying system: a review

4.1. Passive mode (natural convection) solar dryer

Shove [19] reviewed the types of flat plate collectors employed in grain drying. The suspended plate collector in which air flows along both sides of the absorber plate is slightly more complicated but is credited to be more efficient than the bare or covered plate collectors. Sidewall collectors, integrated into the drying bin wall have received considerable attention and development [20,21]. However, these wall collectors are expensive and have a useful life of only two or three seasons. Keener et al. [22] and Chau et al. [23] presented interesting configurations of plastic film solar collectors of various shapes. Also other types of solar collectors including focusing collectors have been treated by Duffle and Beckman [24] and Daniels [25].

Sodha et al. [14] developed a theoretical and experimental study of the solar cabinet dryer. The experimental results has shown that, on typical summer days (1–2 June), high moisture content fruit—mango flesh, with ~95% initial moisture content and ~1 cm layer thickness dries up to ~13% final moisture content in 12 sunshine hours. It was also concluded that the cabinet type driers were very useful for domestic applications for drying fruits and vegetables (i.e. high moisture content products) in developing countries. The over-all efficiency in open sun drying is much less than that of the cabinet type drier and quality of product is maintained in only the cabinet type drier (Fig. 8).

Later Ezeike [26] designed a modular drying system consisting of three functional units, namely a triple-pass flat plate air collector, a drying cabinet, and a dehumidification chamber. The flat plate collector was 190-cm long, 122.5-cm wide and 23.5-cm deep externally and incorporates two absorbers separated by about 6 cm. Air flows below the bottom absorber during the first

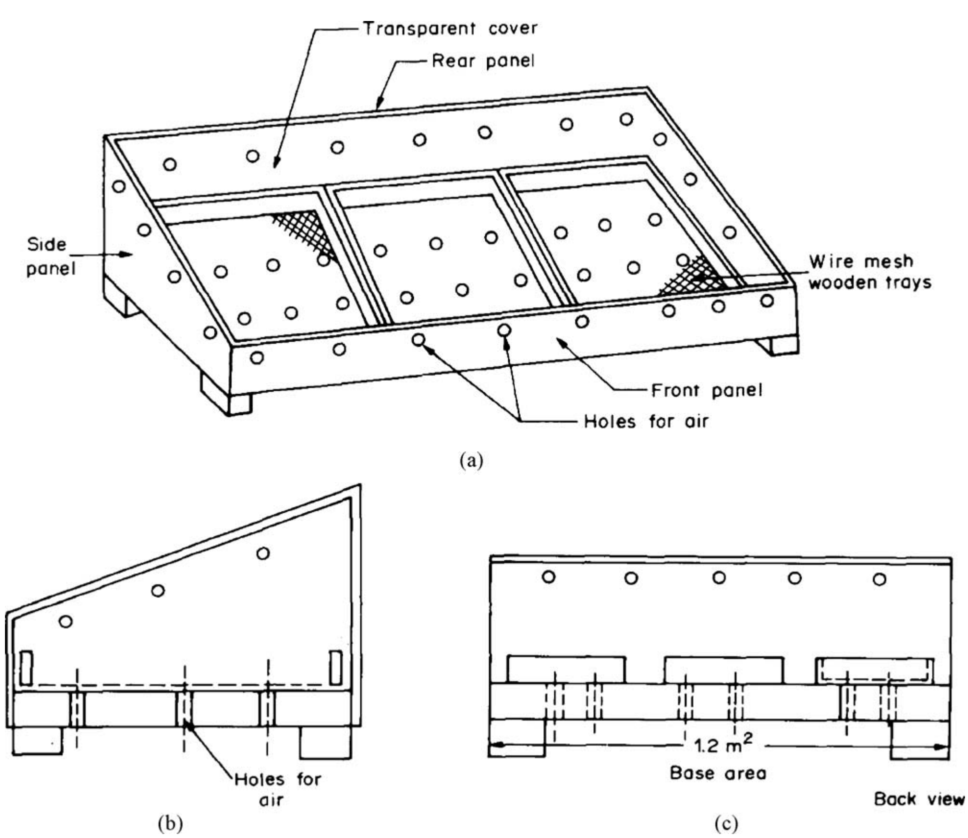


Fig. 8. Experimental setup of a cabinet type drier.

pass, then in the opposite direction and finally through the air spaces between the glazing and top absorber plate into a mixing chamber and a drying chamber; the top air space was divided into two compartments with baffles installed to distribute the air over the collector surface. The drying cabinet has two wall collectors located on the east–west line to provide additional heat gain and trays spaced equally on spacers. The dehumidification chamber was a rectangular box fitted with three perforated trays containing the desiccant, silica gel. That was used to sustain the drying process during periods of low insolation. The results showed that the outlet temperatures ranged from 90 to 101 °C on clear days and at velocities of up to 3.5 m s^{-1}. Thermal analysis of the collector yielded average efficiencies of 73–81%. There was a steep temperature gradient between the top compartment, where temperatures were quite high, and the bottom compartment, where temperatures were only 2–6 °C above ambient. This helped to minimize heat losses to the environment. The thickness of insulation necessary to maintain the same level of heat loss was calculated and the cost involved shown to be much greater than the additional cost of providing a second absorber and the associated baffles. Results of the drying tests with rice paddy and yam slices showed that the system dried rice paddy at a layer density of 7.4 kg m^{-1} from 25.93% (w.b., wet basis) to 5.31% (w.b.) in 10 h and yam slices at a layer density of 5 kg m^{-2} from 64.90% (w.b.) to 10.66% (w.b.) in 31 h. The control experiment at prevailing ambient conditions required 2 days and 4 days, respectively, to attain the same moisture levels. The arrangement of the units (Fig. 9) allow the dryer to operate in the indirect mode when it was receiving air either from the collectors or the dehumidification chamber, the latter being used essentially at night and during periods of low insolation.

Fig. 10 illustrates an indirect solar maize dryer by Othieno, Grainger and Twidell [27–30]. The dryer consisted of a single-glazed passive solar air heater with a 1 m^2 single flat-plate absorber and an air gap of 5 cm from the glazing. The air heater was connected to an insulated drying bin equipped with a chimney. The entire dryer assembly was made from hardboard. To improve efficiency, the air heater was modified with a wider air gap (15 cm) to accommodate three layers of wire-mesh absorber between the glazing and the flat-plate absorber. The dryer was capable of drying 90 kg of wet maize from a moisture content of about 20% wet basis to 12% within 3 days on a bright day.

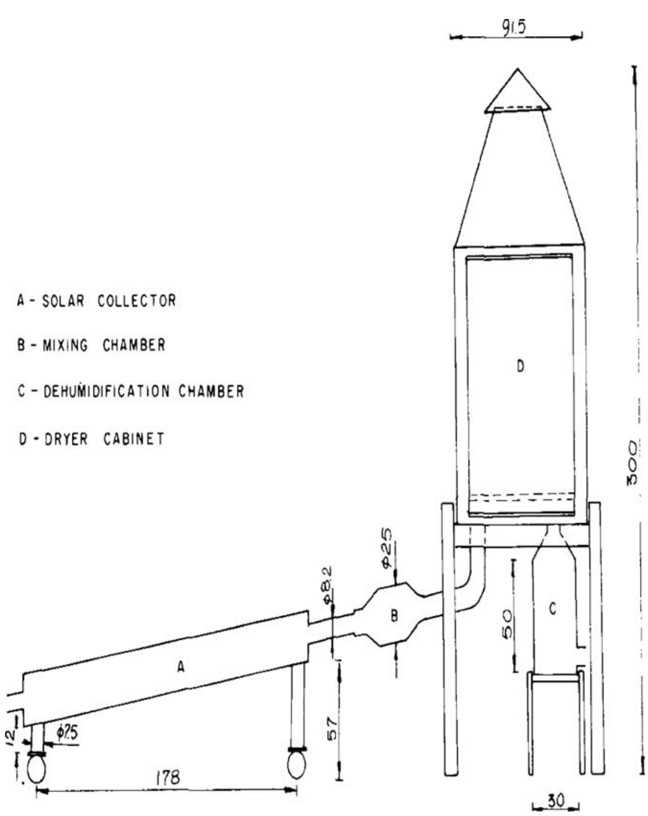


Fig. 9. Experimental setup of the solar dryer (dimensions in cm).

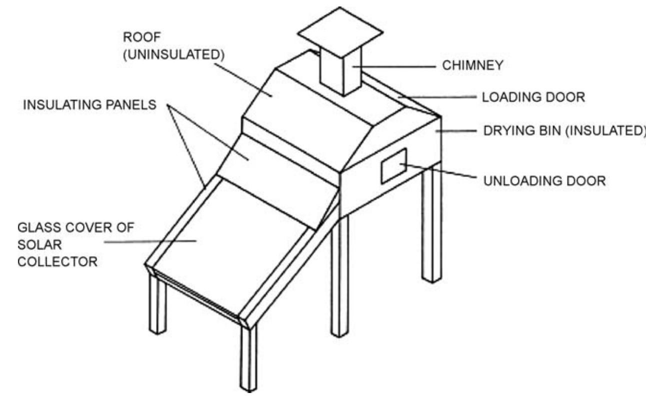


Fig. 10. A distributed-type natural-circulation solar maize dryer.

Gustafsson [31] tested a natural circulation solar-energy cabinet dryer with chimney in Nicaragua (Fig. 11). The dryer had a meshwork floor to allow for air inlet and a chimney at the north end of the cabinet. The chimney was constructed from three vertical wooden poles with an asbestos sheet mounted on the backside and a black PVC foil absorber at the south facing front side. Test results indicated that a better drying efficiency was obtained compared with the traditional passive cabinet dryer without chimney and four times better drying rate than open sun drying.

The earliest form of practically realized natural-circulation solar greenhouse dryers reported was the Brace Research Institute glass-roof solar dryer [32–34]. The dryer (Fig. 12) consisted of two parallel rows of drying platforms (along the long side) of galvanized iron wire mesh surface laid over wooden beams. A fixed slanted glass roof over the platform allowed solar radiation over the product. The dryer, aligned lengthwise in the north–south axis, had black-coated internal walls for improved absorption of solar radiation. A ridge cap made of folded zinc sheet over the roof provides an air exit vent. Shutters at the outer sides of the platforms regulated the air inlet.

Ezekwe [35] reported a modification of the typical designed cabinet dryer (Fig. 13) was equipped with a wooden plenum to guide the air inlet and a long plywood chimney to enhance natural-circulation. This dryer was reported to have accelerated the drying rate about five times over open sun drying.

Das and Kumar [36] designed a prototype, low cost and simple solar dryer coupled with a vertical flat plate collector chimney for drying 20 kg of field harvest high moisture paddy. This unit consisted of an inclined collector (20.6°), a batch dryer and a vertical collector chimney all joined in series and positioned due south. The absorber and cover for both collectors were I m^2 (2 m × 0.5 m) matt black painted corrugated G.I. sheet and 3-mm polymethyllmethacrylate (PMMA), respectively. The experiments were conducted during the winter months. The 20-kg field harvested paddy took 9 h to reduce the moisture content from 31 to 13% (d.b.), a saving of 7 h compared to open field sun drying. Author also concluded that drying system can also be successfully

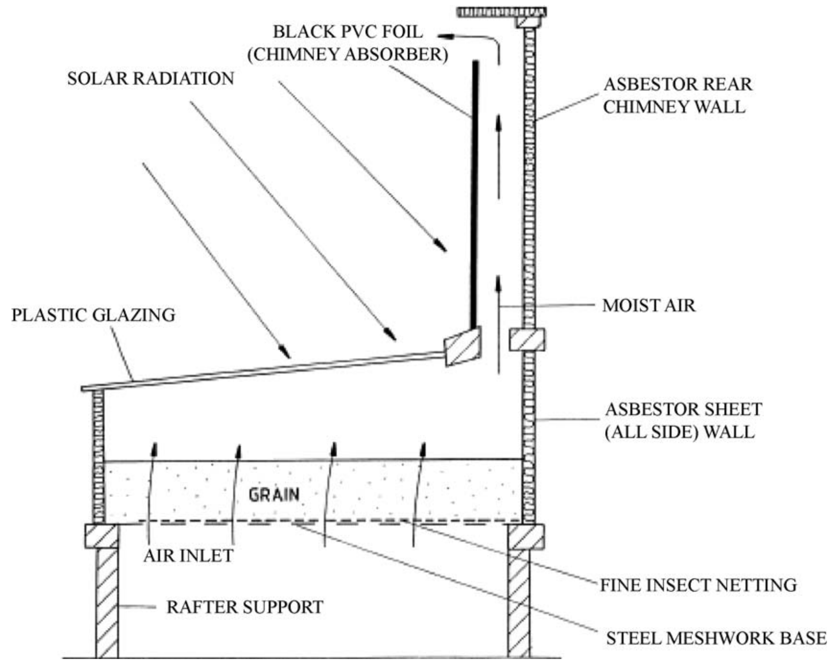


Fig. 11. A natural-circulation solar-energy cabinet dryer with chimney.

used for the drying of other grains, vegetables, fruits and small fishes efficiently, effectively and economically with acceptable quality of the final products.

Pande and Thanvi [37] designed, developed and tested a solar dryer cum water heater (Fig. 14). The system can be used for dehydrating fruit and vegetables or heating water exclusively. The important feature of this new gadget was that the drying process continues even in the night. Experiments have revealed that 10–15 kg of fruit/vegetables can be dehydrated in 3–5 days. As a water heater, it can supply 80 l of hot water of about 60 °C in winter afternoons. It was estimated that the unit can save 418 kWh of electricity as a water heater and, in addition, 500 kg of fruits or vegetables can be dehydrated in a year.

Ayensu [38] designed a low-cost, low-temperature and simple to operate solar dryer was constructed to dehydrate farm produce. Fig. 15 shows a general view of the dryer, consisting of collector with rock storage system, drying chamber and chimney, which was constructed using local materials of wood, scrap metals and glass sheets. The food bed was constructed from a double layer of chicken wire mesh with a fairly open structure to allow drying air to pass through the food sample, but prevent the pieces of food items from falling into the plenum chamber. Access to the drying chamber was via three removable wooden panels made of 1.27-cm plywood, which overlapped each other to prevent air leakages

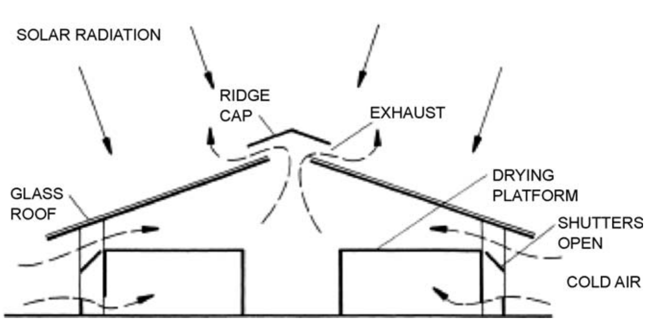


Fig. 12. Natural-circulation glass-roof solar-energy dryer.

when closed or inserted. The top glazing on the drying chamber provided additional heating and also served as an inspection port. The solar collector could transfer 118 W m^{-2} thermal power to the drying air. The thermal exchanges within the dryer were determined from a psychometric chart. Ambient air at 32 °C and 80% relative humidity (RH) could be heated to 45 °C at 40% RH for drying. The crops were dried to a final moisture content of <14% and were preserved for a period of 1 year without deterioration. The low-temperature drying system ensured the viability of the seeds for planting. The designed system can be used to dry food crops (cassava, pepper, okro, groundnuts, etc.). It took nearly two times longer to dehydrate crops by open-air sun drying compared to the solar dryer.

Ekechukwu and Norton [39] designed and developed a natural solar dryer which is suitable for the drying of most crops (Fig. 16). The results from the experimental facility have demonstrated the superior drying characteristics of integral-type, natural-circulation solar-energy dryers over traditional open sun drying.

Ampratwum [40] developed a solar collector in the form of a prototype solar cabinet dryer in Oman (Fig. 17). Experiments have been carried out to evaluate the dryer as a system for harvesting solar energy. The dryer was operated without a load for 28 days from mid-April to the end of May 1996. For the period of operation the dryer attained an average temperate of 81 °C within a 7 h period from 8:00 to 15:00 h. Starting with an average initial temperature of 34 °C at 8:00 h the drying chamber temp rose steeply to 68 °C at 9:00 h and then to 82 °C at 10:00 h. After 10:00 h, the temperature remained approximately constant at 83–84 °C till 15:00 h there was no significant difference between the temperatures from 10:00 till 15:00 h.

Nijmeh et al. [41] were studied the drying behavior of food wastes for utilization as animal feed through the two solar dryers manufactured from locally available materials under Jordanian climatic conditions (Figs. 18 and 19). They reported that the solar boiler dryer is more efficient than the radiative–convective dryer for producing animal feed in terms of both quality and quantity. The nutritious values of the end products from the dryers were

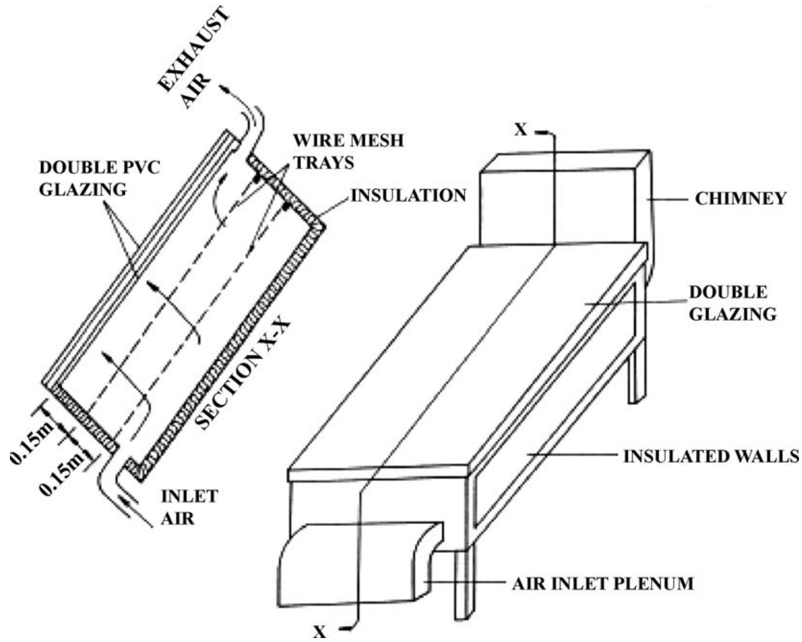


Fig. 13. A modified natural-circulation solar-energy cabinet dryer.

found to be within the international recommended values used for feeding chickens.

El-Sebaii et al. [42] designed, constructed and investigated a indirect type natural convection solar dryer experimentally under Tanta prevailing weather conditions (Fig. 20). The system consisted of a flat plate solar air heater connected to a cabinet acting as a drying chamber. The air heater was designed to be able to insert various storage materials under the absorber plate in order to improve the drying process. Sand was used as the storage material. Drying experiments have been conducted with and without storage materials for different spherical fruits, such as seedless grapes, figs and apples, as well as vegetables, such as green peas, tomatoes and onions. The solar irradiance, temperature distribution in different parts of the system, ambient temperature and relative humidity of the inlet and outlet drying air has been recorded.

Pangavhane et al. [43] developed a new natural convection solar dryer consisting of a solar air heater and a drying chamber (Fig. 21). This system can be used for drying various agricultural products like fruits and vegetables. The grapes were successfully dried in the developed solar dryer. The qualitative analysis showed that the traditional drying, i.e. shade drying and open sun drying, dried the grapes in 15 and 7 days, respectively, while the solar dryer took only 4 days and produced better quality raisins. The drying time of the grapes could be reduced by 43% compared to the open sun drying.

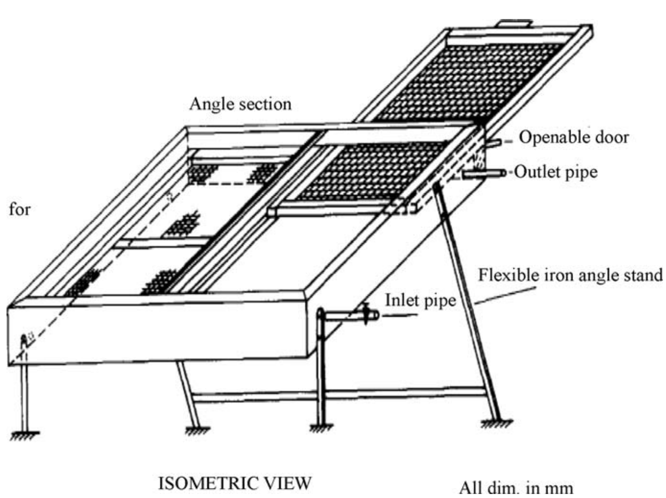
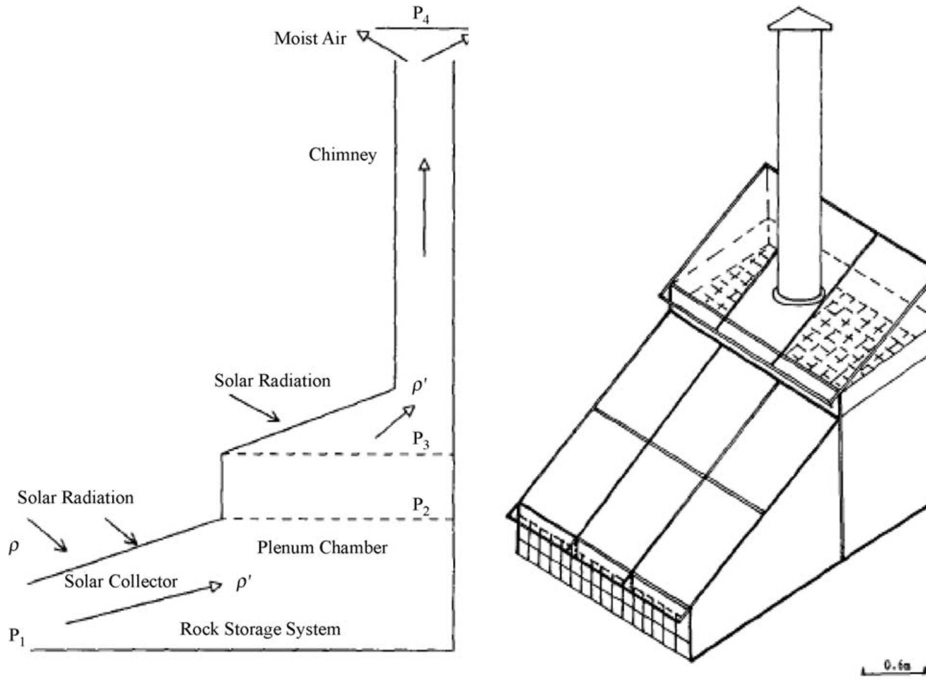


Fig. 14. Experimental setup of solar dryer cum water heater.

Enibe [44] designed a passive solar powered air heating system for the crop drying and poultry egg incubation consists of a single-glazed flat plate solar collector integrated with a phase change material (PCM) heat storage system (Fig. 22). The PCM is prepared in modules, with the modules equi-spaced across the absorber plate. The spaces between the module pairs serve as the air heating channels, the channels being connected to common air inlet and discharge headers. The system was tested experimentally under daytime no-load conditions at Nsukka, Nigeria, over the ambient temperature range of 19–41 °C, and a daily global irradiation range of 4.9–19.9 MJ m^{-2}. These results showed that the system can be operated successfully for crop drying applications.

Singh et al. [45] developed a solar dryer to enable Indian farmers to add value to their produce by drying it at farm itself (Fig. 23). It can also be used in cottage industries in remote places. The dryer had a multi-shelf design with intermediate heating, passive, integral, direct/indirect and portable solar dryer. Intermediate heating of air in-between trays results in uniform drying in all the trays. Since the dryer at the farm is not likely to be used throughout the year, it has been made portable. A novel feature of this dryer is that the product can be dried under shade or otherwise as per requirement. The design is low cost to make it economically viable. The maximum stagnation temperature was 75 °C in the month of November at Ludhiana (31°N).

Li et al. [46] examined the possibility of using a solar drier for drying (Fig. 24), a solar device, consisting of a greenhouse-like drying chamber and 6 m^2 of air collectors, was developed and examined in this study. Experiment showed that the solar drying of the salted greengages was very effective, and the drying period was shortened to about 15 days from 48 days of the traditional sun



(a) (b)

Fig. 15. (a) Schematic diagram of fixed bed dryer with solar collector, plenum chamber, drying chamber and chimney General view of the dryer and (b) General view of the dryer.

drying. It was unexpectedly found that using the developed device could eliminate a process that takes 20 days to desalt the salted greengages as required in the traditional production of preserved greengages. This means that the use of the solar drier could significantly shorten the production period of preserved greengages. It was also observed that using the solar drier could prevent regaining moisture by the salted greengages at night or in rainy days during the drying period. To improve the thermal efficiency, it is advisable to spread fully wet salted greengages on the top two meshes and semi-dry ones on other meshes of the drying chamber at the late stage of the drying process.

Mwithiga and Kigo [47] designed and tested a small solar dryer with limited sun tracking capabilities (Fig. 25). The dryer had a mild steel absorber plate and a polyvinyl chloride (PVC) transparent cover and could be adjusted to track the sun in increments of 15°. The performance was tested by adjusting the angle the dryer made with the horizontal either once, three, five or nine times a day when either loaded with coffee beans or under no load conditions. The temperature distribution in the plenum and also the drying rate of parchment coffee were determined. The temperature inside the plenum chamber could reach a maximum of 70.4 °C and the dryer could lower the moisture content of coffee beans from 54.8% to below 13% (w.b.) in 2 days as opposed to the 5–7 days required in sun drying. Tracking the sun though allowing a faster rate of drying did not offer a significant advantage in terms of length of drying duration.

Koyuncu [48] designed, constructed and tested two different types of natural-circulation greenhouse crop dryers (Figs. 26 and 27). Each dryer mainly consisted of a framework constructed from black-coated metal bars, corrosion-resistant plastic mesh and a black-coated solar radiation absorber surface. The frameworks of the dryers were clad with clear polyethylene sheet on the all sides. The cladding at rear side was arranged to allow put the moist products into the drying chamber or get dried product from there. The clear plastic cladding at the bottom edge of the front side and rear side was also arranged to allow air to flow into the chamber, while the rectangular stream at the top of the end served as the exit for the moist exhaust air. The dryers were tested in the summer conditions. All dryers were experimented without crops (no product loaded) and with crops (pepper loaded). The dryers were also tested with chimney constructed from a galvanized iron sheet and without chimney in order to determine the effect of the chimney on the airflows. In addition, pepper was dried in the open-sun drying in order to compare the greenhouse dryers with open air drying. The results of the study show that the use of natural-circulation greenhouse dryers for drying agricultural products, was 2.5 times more efficient than open air drying and using black coated solar radiation absorber surface and chimney improve the performance of these dryers.

Singh et al. [49] developed a multi-shelf domestic solar dryer for drying various products at home under hygienic conditions with the self guarantee of adulteration free product. This solar dryer was multi-shelf design, consisting of three perforated trays arranged one above the other. The drying air flows through the product by natural circulation. One of its novel features was variable inclination to capture more solar energy in different seasons. Another novel feature was the option to dry product under shade or without shade as per requirement. The rate of drying was uniform in all the trays due to heating of the air by solar energy in between the trays. The maximum stagnation temperature of this solar dryer was found to be 100 °C in the month of November at Ludhiana (31°N). The domestic solar dryer was a small-sized, natural circulation, solar dryer (Fig. 28). Most of the products that were used in powder form in domestic kitchen, e.g. chillies, garlic, ginger, mango powder, coriander, onion, fenugreek leaves, etc., were used in small quantities of the order of a few kilograms per year. Keeping these requirements in view, the aperture area of this dryer has been kept at 0.36 m^2 such that it was capable of drying

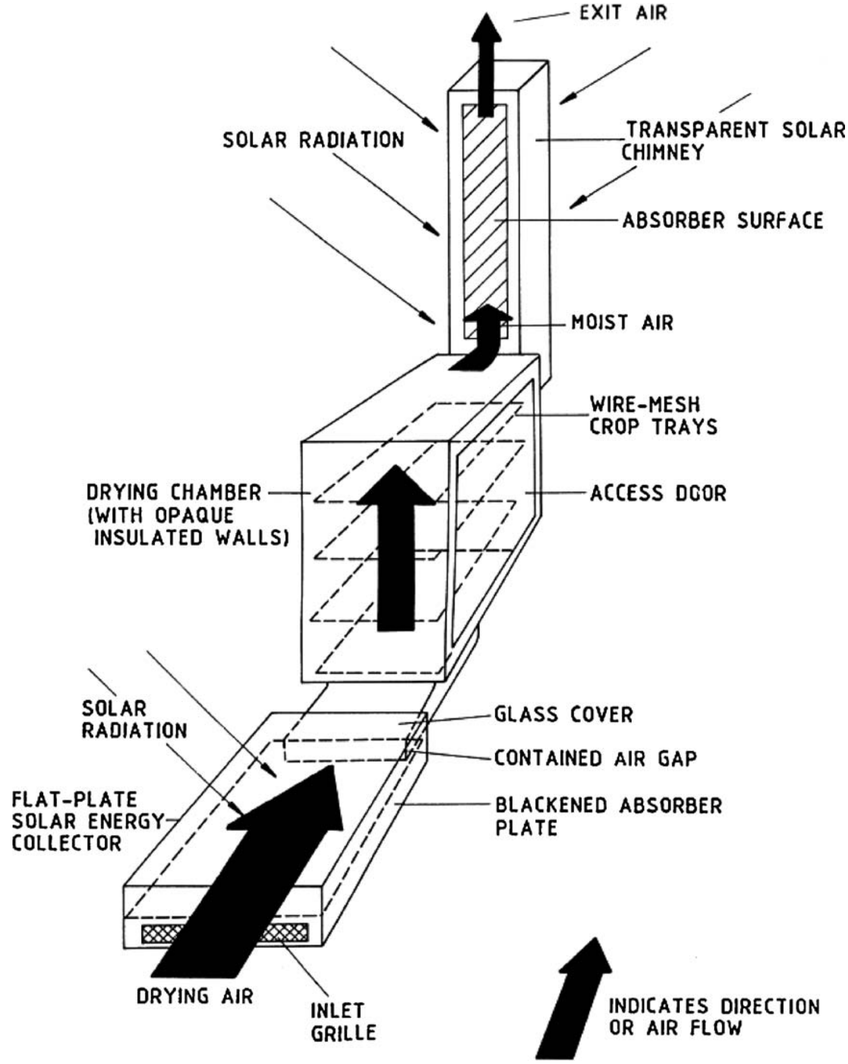


Fig. 16. Schematic illustration of a distributed (indirect) type natural-circulation solar-energy dryer.

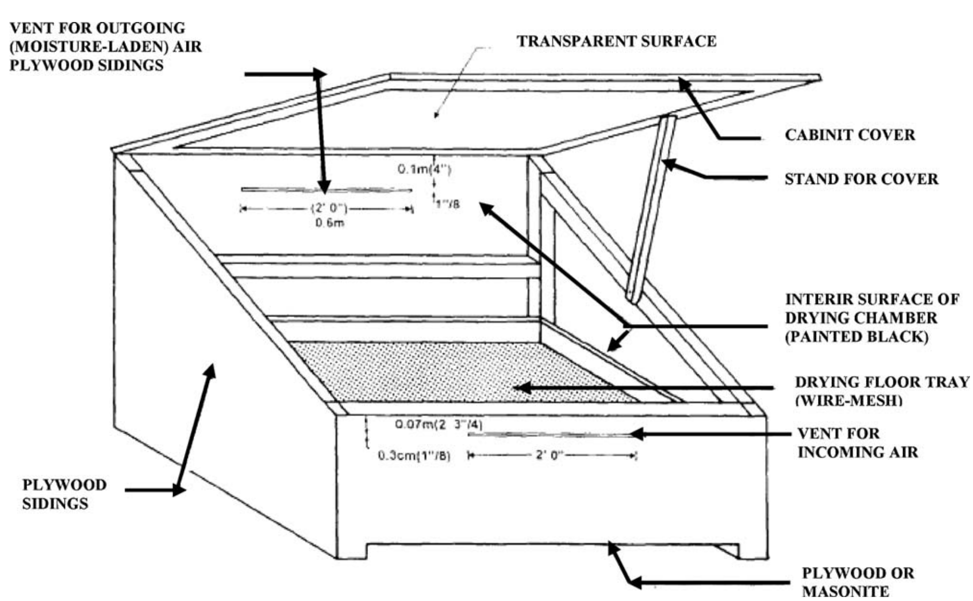


Fig. 17. Solar cabinet dryer with open cover.

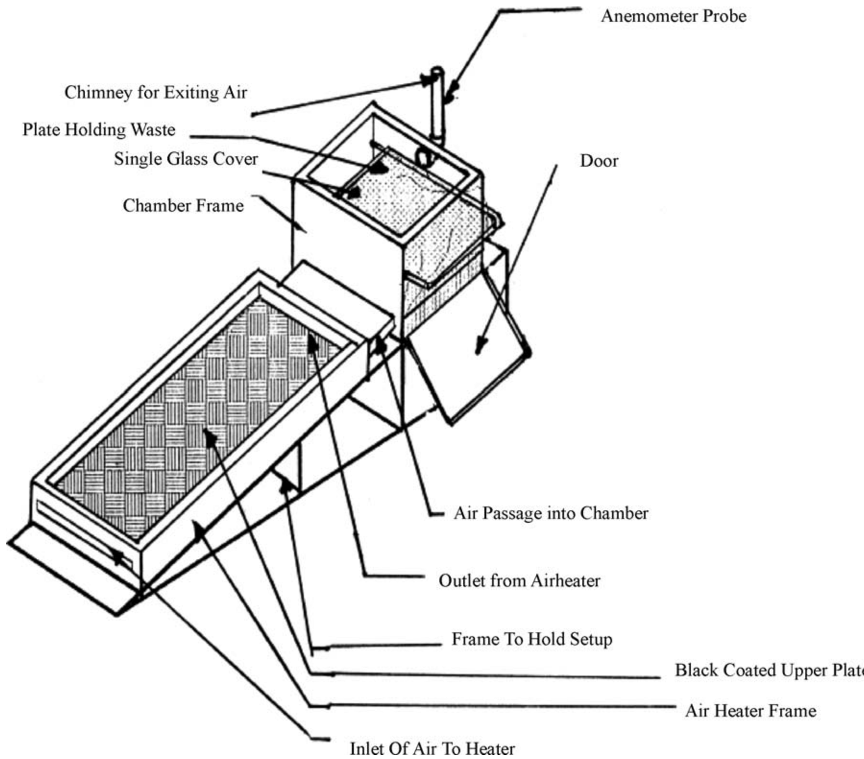


Fig. 18. A schematic diagram of the radiative–convective dryer.

about 1 kg of fresh product per day. The use of this dryer at the domestic level has shown that this capacity was quite suitable for northern Indian households.

Prasad et al. [50] developed a hybrid dryer for drying at village scale. The use of petroleum fuel or electricity for drying of agricultural produce is an expensive process at village scale in developing countries. Therefore, an appropriate technology for drying of agricultural produce has been developed and its performance for the drying of turmeric rhizomes has been evaluated. A direct type natural convection solar cum biomass

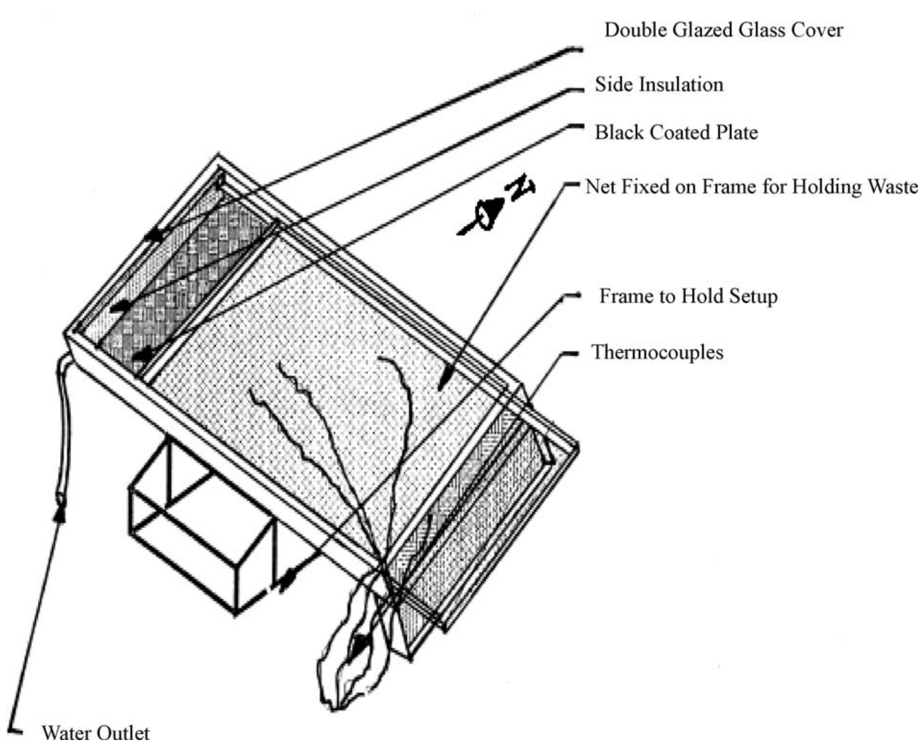


Fig. 19. A schematic diagram of the boiler dryer.

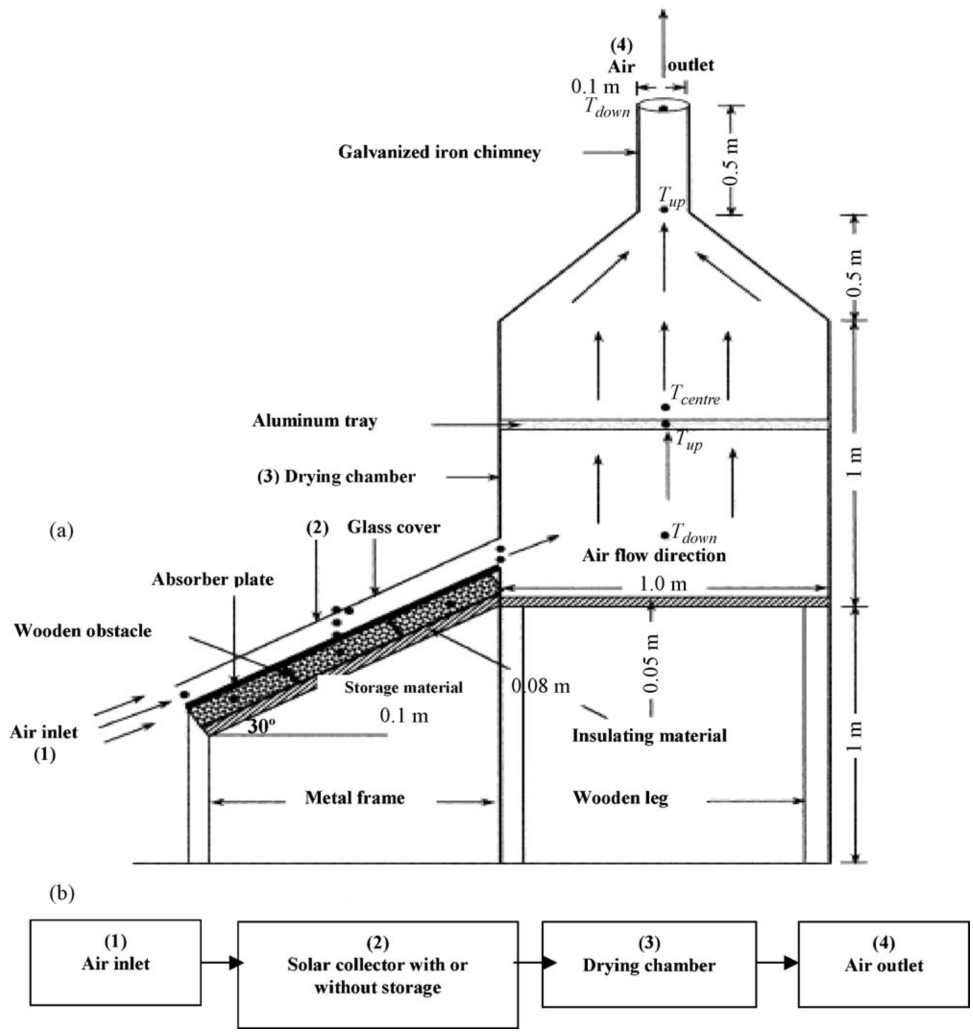


Fig. 20. (a) Cross-sectional view of the indirect type natural convection solar dryer; (●) thermocouples positions. (b) Airflow diagram.

drier was developed. The system was capable of generating an adequate and continuous flow of hot air temperature between 55 and 60 °C. Turmeric rhizomes were successfully dried in developed system. Dried turmeric rhizomes obtained under solar biomass (hybrid) drying by two different treatments, viz., water boiling and slicing were similar in quality with respect to physical appearance like colour, texture, etc., but there is significant variation in volatile oil. The quantitative analysis showed that the traditional drying, i.e., open sun drying had taken 11 days to dry the rhizomes while solar biomass drier took only 1.5 days and produced better quality produce. The efficiency of the whole unit obtained was 28.57%. The solar biomass drier was fabricated for drying of turmeric rhizomes and other such produce. The detail of the drier is shown in Fig. 29.

Madhlopa and Ngwalo [51] designed, constructed and evaluated an indirect type natural convection solar dryer with integrated solar collector–storage and biomass-backup heaters. The major components of the dryer were biomass burner (with a rectangular duct and flue gas chimney), collector–storage thermal mass and drying chamber (with a conventional solar chimney). The thermal mass was placed in the top part of the biomass burner enclosure. The dryer was fabricated using simple materials, tools and skills, and it was tested in three modes of operation (solar, biomass and solar–biomass) by drying twelve batches of fresh pineapple with each batch weighing about 20 kg. Results showed that the thermal mass was capable of storing part of the absorbed solar energy and heat from the burner. It was possible to dry a batch of pineapples using solar energy only on clear days. Drying proceeded successfully even under unfavorable weather conditions in the solar–biomass mode of operation. In this operational mode, the dryer reduced the moisture content of pineapple slices from about 669 to 11% (d.b.) and yielded a nutritious dried product. The average values of the final-day moisture pickup efficiency were 15%, 11% and 13% in the solar, biomass and solar–biomass modes of operation, respectively. It appears that the solar dryer was suitable for preservation of pineapples and other fresh foods. An indirect solar dryer was designed and constructed with a biomass backup burner (Fig. 30). The dryer has a solar collector, drying cabinet and backup heater. The collector of the dryer has a horizontal concrete absorber that was painted matt black on its top part and integrated to the rock pile (Fig. 31).

4.2. Active mode (forced convection) solar dryer

Arata and Sharma [52] developed a simple design using simple tools and relatively cheap and locally available materials by small scale industries using solar air heater with simple design. Fig. 32 shows the solar air collector with cabinet dryer for fruit drying applications. Author also discussed with farmers themselves, using cheap and locally available materials by small-scale industries.

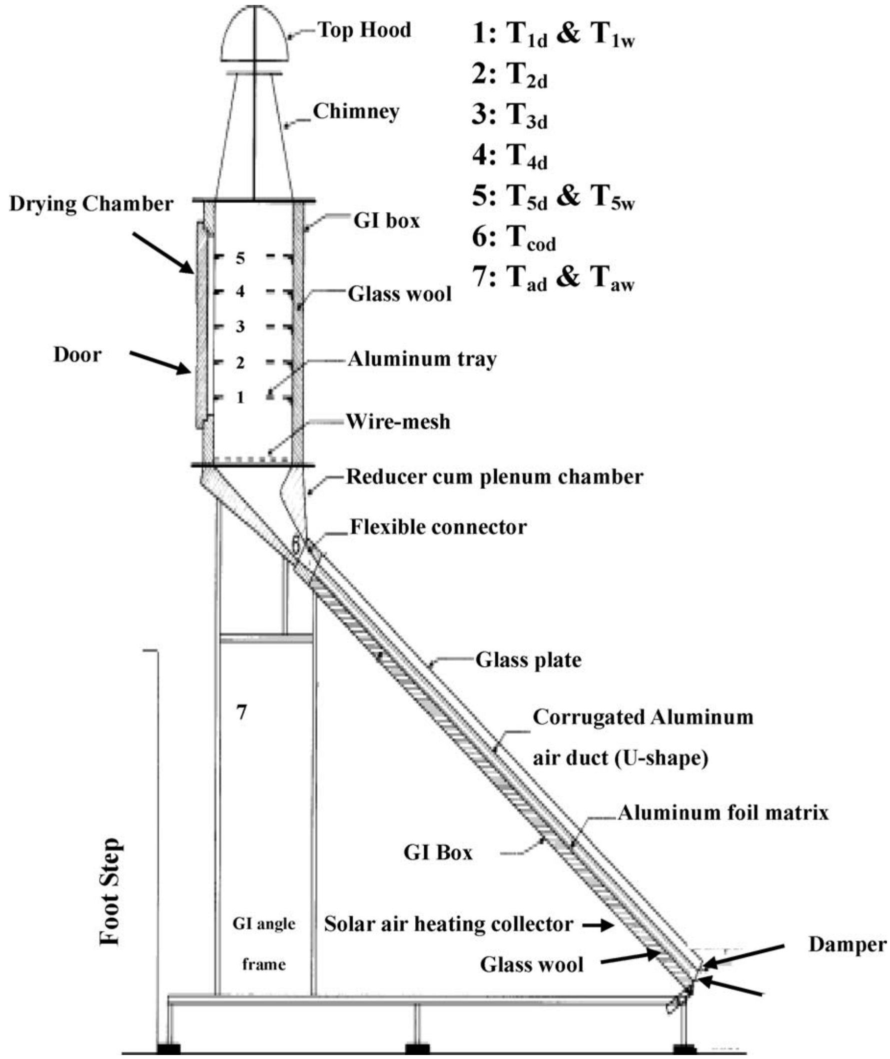


Fig. 21. Sectional details of natural convection solar dryer.

They also concluded that kind of simple design mechanism can be very fruitful for the farmers.

Pawar et al. [53] designed and fabricated a large-scale forced convection solar drying system presented in Fig. 33. Drying system comprising an array of forty solar collectors and three drying cabinets with a blower. It was shown that use of this type system was feasible and had an ability to save large amounts of fuel. It keeps the product clean and it was dried in a shorter period than in open sun drying. It was found that forced convection solar drying systems were suitable in food and chemical industries where large scale drying is required.

Fig. 22. Photograph of the air heating system. (A) Collector assembly with energy storage and air-heating subsystems and (B) heated space.

Tiris et al. [54–57] developed a new solar dryer, which consisted of a solar air heater and a drying chamber. The present drying system was successfully tested using sultana grapes, green beans, sweet peppers and chilli peppers. The traditional sun-drying experiments were employed and compared with the solar-drying experiments. It was shown that the use of this type of solar dryer reduced the drying time significantly and essential provided better product quality. The thermal efficiencies of both the solar air heater and the drying section as a function of typical physical parameters and the experimental results for different food products at different airflow rates are discussed. Fig. 34 shows schematic representation of the drying system. The results of this study indicated that the drying system had thermal efficiencies between 0.3 and 0.8 during drying experiments and that the higher flow rates increase the overall drying performance and especially efficiency.

Mumba [58,59] designed and developed a solar grain dryer with photovoltaic powered air circulation (Fig. 35). The important

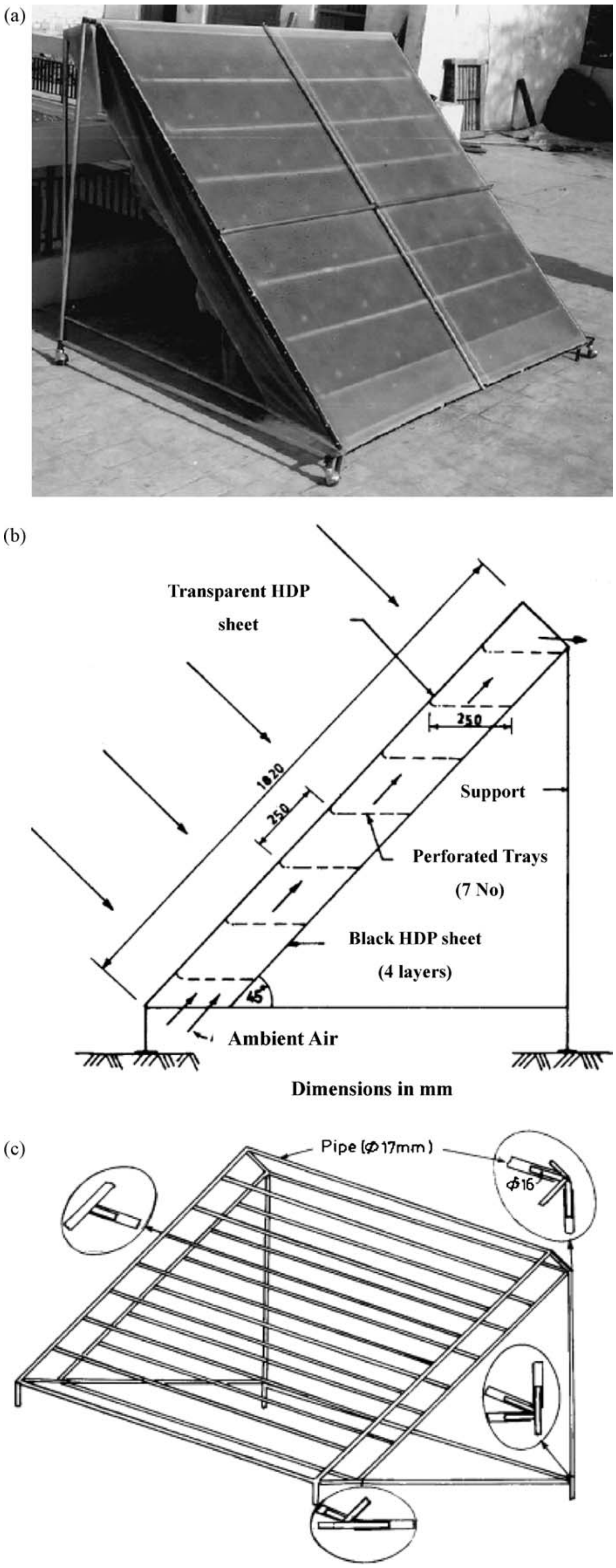


Fig. 23. (a) Photograph of PAU portable farm solar dryer. (b) Side view of the dryer. (c) Details of multi-tray rack.

feature in this new dryer was the use of photovoltaic solar cells incorporated in the solar air heater section to power a d.c. fan. This photovoltaic powered air circulation induces passive control over the drying air temperature. The dryer can dry 90 kg maize grain per batch from an initial moisture content of 33.3% dry basis to under 20% dry basis in just 1 day. The controlled drying air temperature has an upper limit of 60 ± 3 °C to prevent grain overheating and cracking. The dryer has been found to be cost-effective with a payback period of less than 1 year. Compared with the traditional sun drying method, drying with the dryer was found to be a viable option with many benefits, such as a protected drying environment, improved dried product quality and increased throughput. The drier is suitable for rural farm applications where grid electricity and fossil fuel are either nonexistent or extremely expensive for the average farmer.

Thoruwa et al. [60,61] designed and developed a prototype solar crop dryer shown in Fig. 36. The desiccant bed was a shallow tray with a perforated bottom, which held 32.5 kg of solid bentonite $CaCl_2$ desiccant packed into 250 g bags. The desiccant was formed from a mixture of bentonite, $CaCl_2$, vermiculite and cement in the ratio 6:1:2:1 by weight, processed at 50 °C for 24 h and then dried at 200 °C for 24 h. Tests indicated that this mass of desiccant should be able to hold up to 14.6 kg of water. Above the bed a double Tedler glazing panel was placed. The panel and the desiccant bed were inclined at 15° to the horizontal for optimal solar-energy collection and protection from the ingress of rain. The dryer system contained a grain bed but for these tests it was empty, as the aim was to assess its ability to deliver dehumidified air to an external application. During the daytime, ambient air was drawn through the entry port by a small fan, passed through the desiccant bed and then exhausted via valve A, valve B remained closed. At night, valve A was closed and valve B was opened; the air that passed through the desiccant bed was exhausted by valve B to the atmosphere; in practical use, it would be delivered to the grain store. The fan used in the prototype was powered from a 12-V battery, charged by a small photovoltaic panel mounted alongside; its power demand was in the range 5–10 W.

Sarsilmaz et al. [62] conducted experiments on drying of apricots in a newly developed rotary column cylindrical dryer equipped with a specially designed air solar collector was investigated to and optimum drying air rate and rotation speed of dryer, to maintain uniform and hygienic drying conditions and to reduce drying times. Fig. 37 shows the complete drying system. Drying operation is of prime importance which is applicable to almost all the agricultural products.

Condori et al. [63] built and tested a low cost design for a forced convection tunnel greenhouse drier. The main advantages of this drier were: (a) an almost continuous production since some carts with dried product come out of the tunnel every day, while the same amount of fresh product was introduced by the other tunnel extreme; (b) lower labor cost since the product handling was partly mechanized; (c) a conventional heater can be easily installed to keep a constant production rate; (d) the energy consumption was lower than in other drier types; (e) the installation can be used as a greenhouse for small production when it is not used as a drier. Fig. 38 is shown forced convection greenhouse drier with the tunnel.Ivanova and Andonov [64] presented a structure of a dryer using solar energy and heat of geothermal water from a natural field for heating the dryer air. Author also presented a model of the temperature–humidity processes in the dryer chamber using solar energy for heating the air. It also presented an experimental performance of the dryer in "dry experiment" (without moisture) and real drying processes.

Bala et al. [65] conducted some field level experiments on solar drying of pineapple using solar tunnel drier at Bangladesh Agricultural University, Mymensingh, Bangladesh (Fig. 39). The

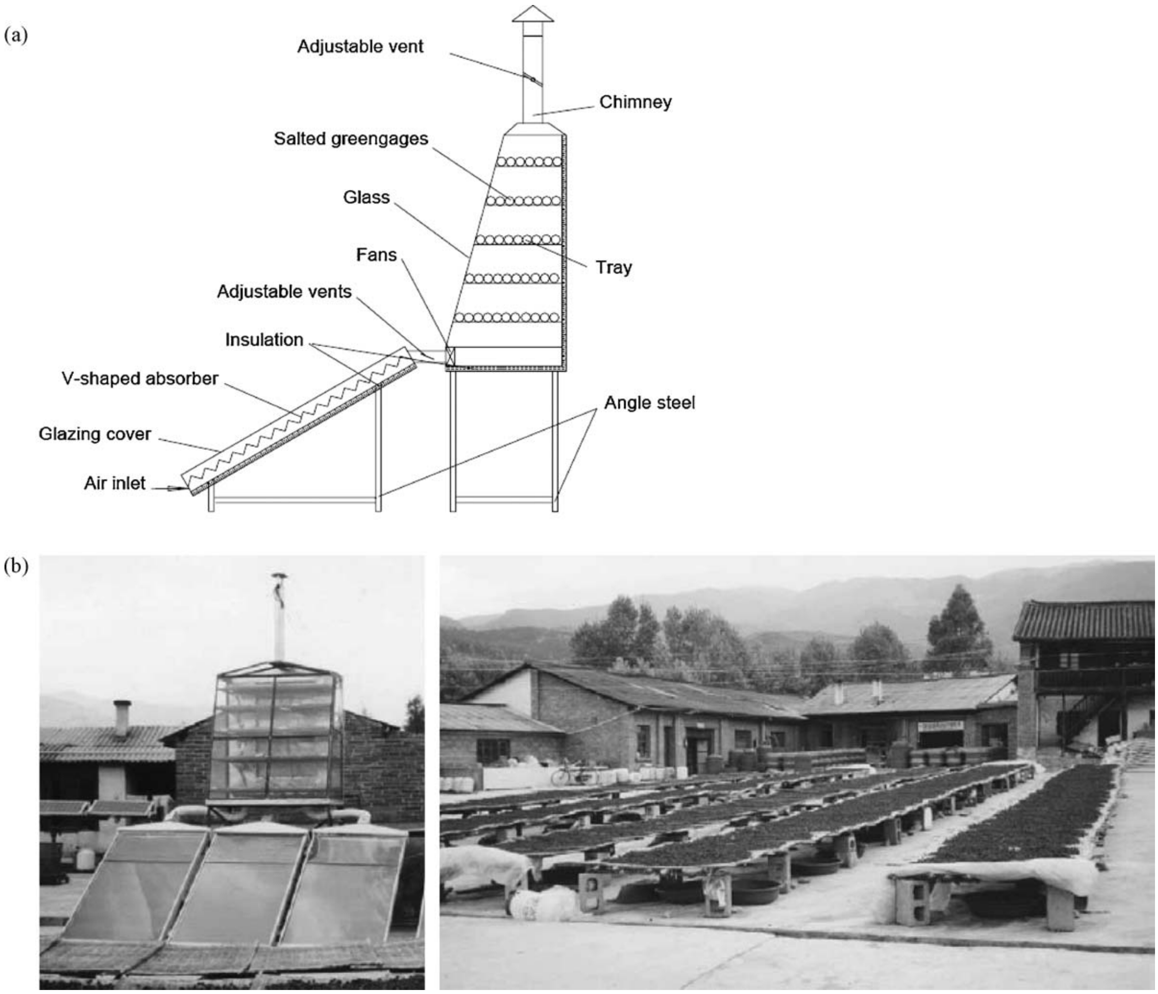
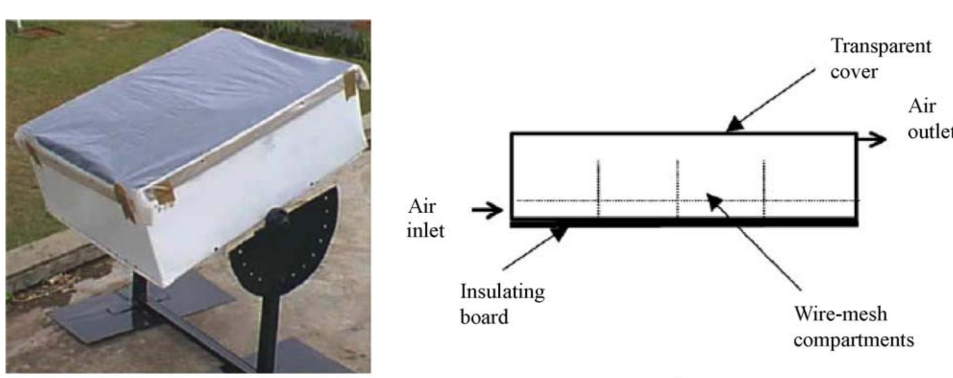


Fig. 24. (a) Cross-sectional diagram of the examined solar drier. (b) Left: photograph of examined solar drier in the experimental site. Right: ground of natural sun drying.

drier consisted of a transparent plastic covered flat plate collector and a drying tunnel connected in a series to supply hot air directly into the drying tunnel using two d.c. fans operated by a solar module. This drier had a loading capacity of 120–150 kg of pineapple and a total of eight drying runs were conducted. In all the cases the use of the solar tunnel drier leads to considerable reduction of drying time in comparison to sun drying. The pineapple being dried in the solar tunnel drier were completely protected from rain, insects and dust, and the quality of the pineapple dried in the tunnel drier was of quality dried products as compared to sun dried products.

Shanmugam and Natarajan [66] designed and fabricated an indirect forced convection and desiccant integrated solar dryer (Fig. 40) to investigate its performance under the hot and humid climatic conditions of Chennai, India. The system consists of a flat plate solar air collector, drying chamber and a desiccant unit. The desiccant unit was designed to hold 75 kg of $CaCl_2$-based solid desiccant consisting of 60% bentonite, 10% calcium chloride, 20%



(a) (b)

Fig. 25. The solar dryer used in drying experiments: (a) pictorial view; (b) cross-section view.

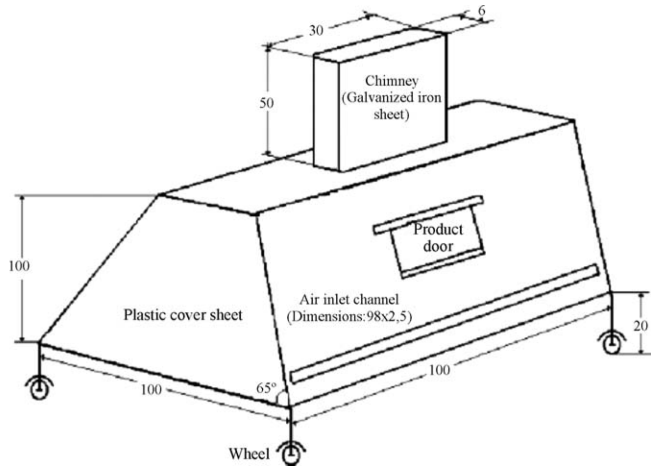


Fig. 26. A simple presentation of M-I.

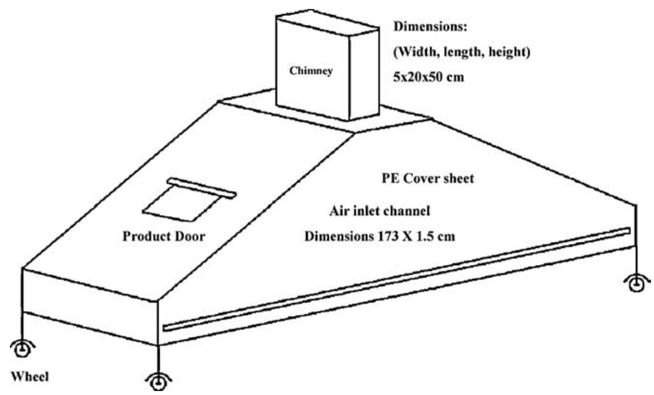


Fig. 27. A simple presentation of M-II.

vermiculite and 10% cement. Drying experiments have been performed for green peas at different airflow rate. The system pickup efficiency, specific moisture extraction rate, dimensionless mass loss, mass shrinkage ratio and drying rate are discussed in this paper.

Shanmugam and Natarajan [67] also investigate the performance of an indirect forced convection and desiccant integrated

Fig. 28. Photograph of domestic solar dryer with door open.

solar dryer for drying green peas and pineapple slices with and without the reflective mirror. The inclusion of reflective mirror on the desiccant bed increases the drying potential considerably. The useful temperature rise of about 10 °C was achieved with mirror, which reduced the drying time by 2 and 4 h for green peas and pineapple, respectively. Also, the pick-up efficiency, drying rate and average dryer thermal efficiency were relatively higher, when compared to solar drying and desiccant integrated drying. Uniform drying in all the trays were achieved with good quality in terms of colour and microbiological decay, when compared to solar drying. Taste of the dried pineapple was satisfactory. The desiccant material was stable even after continuous operation for more than a year. The dryer can be used for drying various agricultural products. It can reduce drying time and improve quality of the dried product. The pictorial view of the experimental setup is shown in Fig. 41.

Hossain and Bala [68] mixed mode type forced convection solar tunnel drier was used to dry hot red and green chillies under the tropical weather conditions of Bangladesh (Fig. 39). The drier had a loading capacity of 80 kg of fresh chillies. Moisture content of red chilli was reduced from 2.85 to 0.05 kg kg^{-1} (d.b.) in 20 h in solar tunnel drier and it took 32 h to reduce the moisture content to 0.09 and 0.40 kg kg^{-1} (d.b.) in improved and conventional sun drying methods, respectively. In case of green chilli, about 0.06 kg kg^{-1} (d.b.) moisture content was obtained from an initial moisture

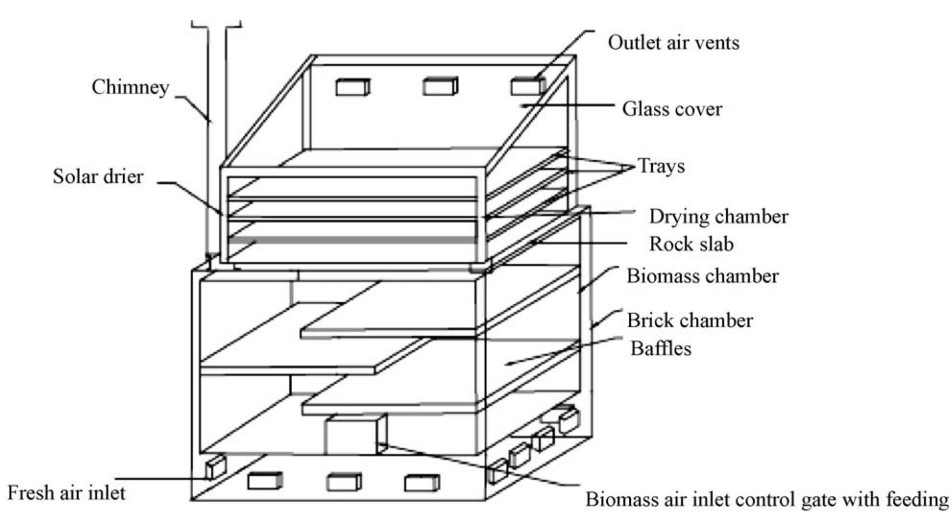


Fig. 29. Schematic diagram of solar biomass drier.

Fig. 30. Perspective view of the solar dryer.

content of 7.6 kg kg^{-1} (d.b.) in 22 h in solar tunnel drier and 35 h to reach the moisture content to 0.10 and 0.70 kg kg^{-1} (d.b.) in improved and conventional sun drying methods, respectively. The use of a solar tunnel drier and blanching of sample led to a considerable reduction in drying time and dried products of better quality in terms of colour and pungency in comparison to products dried under the sun. The solar tunnel drier and blanching of chilli are recommended for drying of both red and green chillies.

Chen et al. [69] conducted an experimental investigation to test a new forced flow solar dryer (Fig. 42) at Kun Shan University, Tainan, Taiwan, ROC consisting of a solar air-heater and a drying chamber. Banana chips was selected as test samples and dried in the present system. The moisture content (wet basis) of banana chips was reduced from 75–85% to 7–8% and thermal efficiency of dryer was 30.86% for the 5 days drying experiments since 9.00 to 16.00 h. The present solar dryer provided better quality and a shorter drying period. Authors also concluded that further research is required to determine technical and economical aspects, and to optimize the solar air-heater.

Al-Juamily et al. [70] tested the performance of a fruit and vegetable solar dryer system at Iraq. The dryer system consisting of three parts (solar collector, solar drying cabinet, and air blower). Two identical air solar collectors having V-corrugated absorption plates of two air passes, a single glass cover was used. The total area of the collectors was 2.4 m^2. The cabinet was divided into six divisions separated by five shelves. Two types of fruit and one type of vegetables were dried during the present work. These were grapes, apricots, and beans. The moisture content of apricot was reduced from 80 to 13% within 1 day and a half of drying. Moisture content of grapes was reduced from 80 to 18% in two and a half days of drying, while that of beans was reduced from 65 to 18% in 1 day only. The results show that the most effective factor on the drying rate was the temperature of the air inside the cabinet. The effect variation of speed of air inside the drying cabinet is small and can be neglected. The relative humidity of air exit from the cabinet was small (between 25 and 30%) and therefore there was no need for high velocity air inside the cabinet. Fig. 43 shows the drying system, which includes collector, drying chamber, and the blower.

Zomorodian et al. [71] introduced a new approach for employing solar radiation as the main source of energy for paddy drying. The drying test rig was designed, fabricated and evaluated. The rough rice solar dryer was a cross-flow and an active mixed-mode type with a new and an efficient timer assisted semi-continuous discharging system. The rig consists of six ordinary solar air heaters, an auxiliary electric heating channel, a drying chamber with an electrically rotary discharging valve and an air distributing system (Fig. 44). The area of each collector was 2 m^2 (totally 12 m^2) and they were installed on a light frame tilted 45° towards the south. The drying system consisted of: an inlet bin, a drying chamber ended with a discharging valve, an outlet bin and a plenum chamber. At the bottom of dryer bed, an electro-mechanical rotary valve was installed which was controlled by

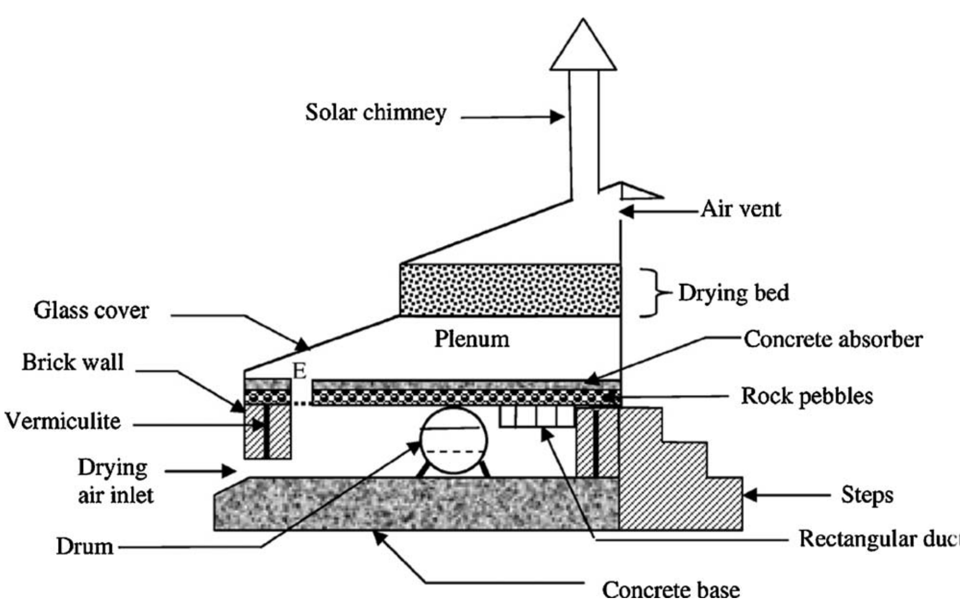


Fig. 31. Cross-sectional view of the solar dryer through the burner, collector, drying chamber and solar chimney.

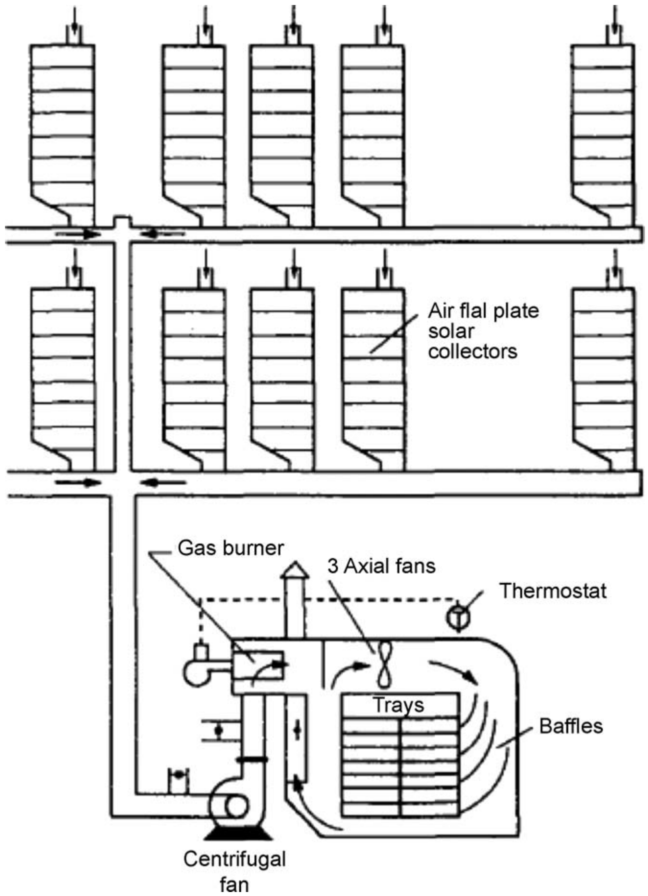


Fig. 32. Solar air collector with cabinet dryer for fruit drying applications.

a timer. The timer activated the rotary valve to operate once a while to discharge the dryer bed semi-continuously. To evaluate the drying system, a local variety of medium size kernel of rough rice was selected to be dried by the dryer. One of the objectives in this research was to evaluate the effect of mass flow rate and interval time of crop discharging on the rate of crop drying by the dryer. The first experiment was conducted with two factors: mass flow rate (three levels), and discharge interval time (two levels).

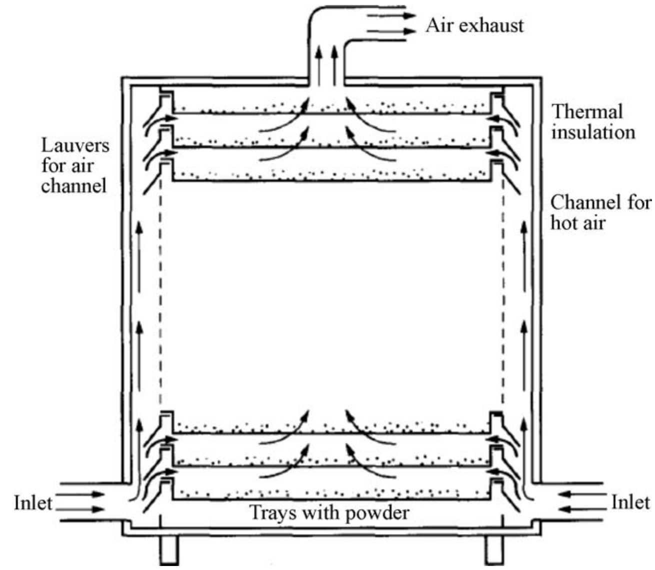


Fig. 33. Schematic diagram of a drying cabinet of custard powder drying system.

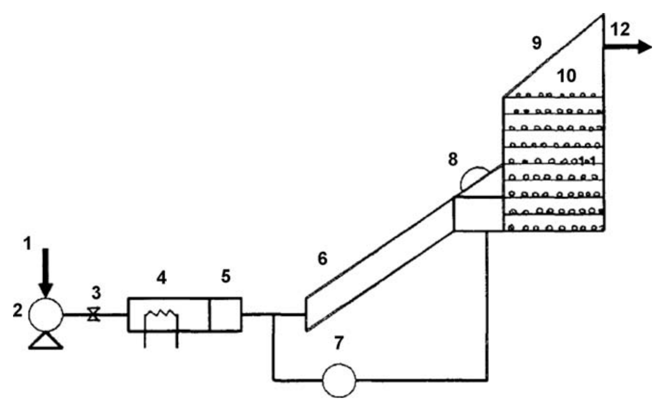


Fig. 34. Schematic representation of the drying system (I-air inlet; 2-fan; 3-valve; 4-electrical heater; 5-flowmeter; 6-solar air heater; 7-pressure transducer; 8-pyranometer; 9-drying chamber; 10-rack; II-product; 12-air outlet).

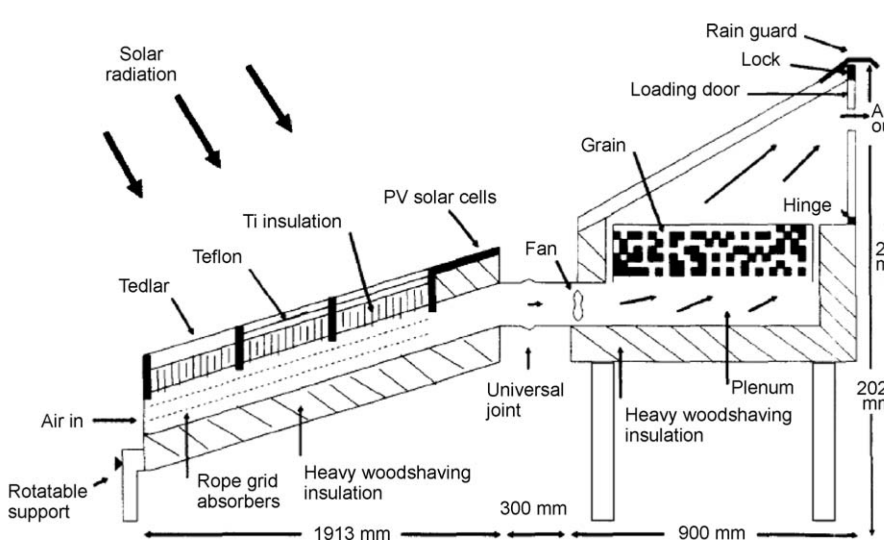


Fig. 35. A solar-grain drier incorporating a photovoltaic-powered d.c. fan.

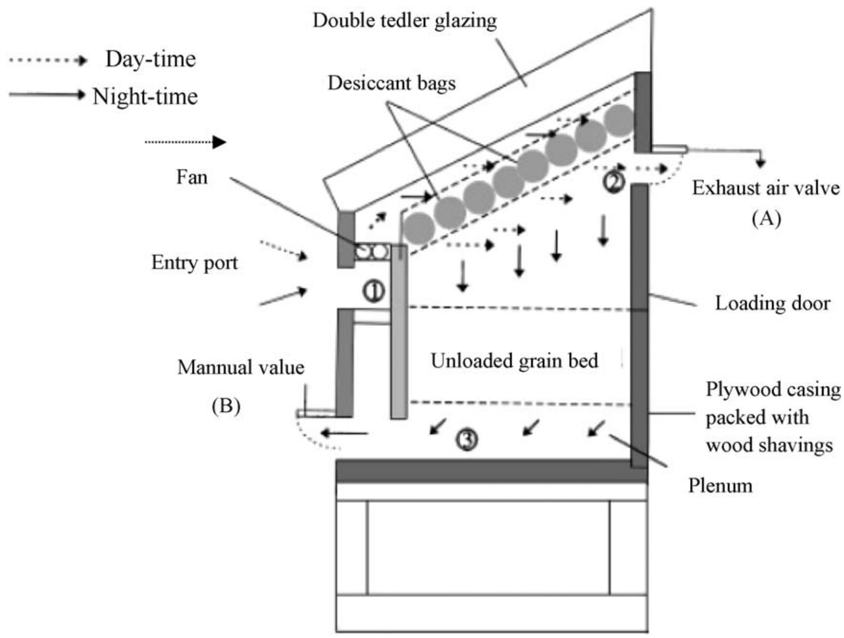


Fig. 36. The prototype integrated desiccant/collector dehumidifier mounted on the crop bin as tested in Kenya (day/night-time operational modes) with the position of three thermocouples numbered.

The second experiment was conducted with three factors: the moisture content of different locations on dryer bed (four levels), mass flow rate (three levels), and discharging interval time (two levels). The dryer capacity, the efficiency of collectors and the overall efficiency of the drying system were evaluated. The maximum overall efficiency of drying system was 21.24% (with average drying air temperature of 55 °C) and the fraction of energy consumed by the auxiliary heating channel during the drying process compared with solar energy was only 6–8%. The maximum capacity of the dryer was about 132 kg of rough rice with initially 27% d.b. down to 13% d.b. final moisture content in 3 h of drying period.

Sarsavadia [72] developed a solar-assisted forced convection dryer for dehydration of onion slices for the controlled conditions of drying air temperatures and airflow rates similar to those employed in commercial onion dehydration. The dryer was also facilitated with recirculation of exhaust air (Fig. 45). The total energy required for drying of onion slices increased with increase in airflow rate and decreased with increase in drying air temperature. For drying of onion slices from initial moisture content of about 86% (w.b.) to final moisture content of about 7% (w.b.), the total energy required per unit mass of water ranged between 23.548 and 62.117 MJ/kg water during without using any recirculation of air. The percent energy contribution by the solar air heater, electrical heater, and blower to the total energy requirement ranged between 24.5% and 44.5%, 41.0% and 66.9%, and 8.6% and 16.3%, respectively.

Sreekumar et al. [73] developed and tested a new type of efficient solar dryer, particularly meant for drying vegetables and fruit, was described. The dryer has two compartments: one for collecting solar radiation and producing thermal energy and the other for spreading the product to be dried (Fig. 46). This arrangement was made to absorb maximum solar radiation by the absorber plate. In this dryer, the product was loaded beneath the absorber plate, which prevented the problem of discolouration due to irradiation by direct sunlight. Two axial flow fans, provided

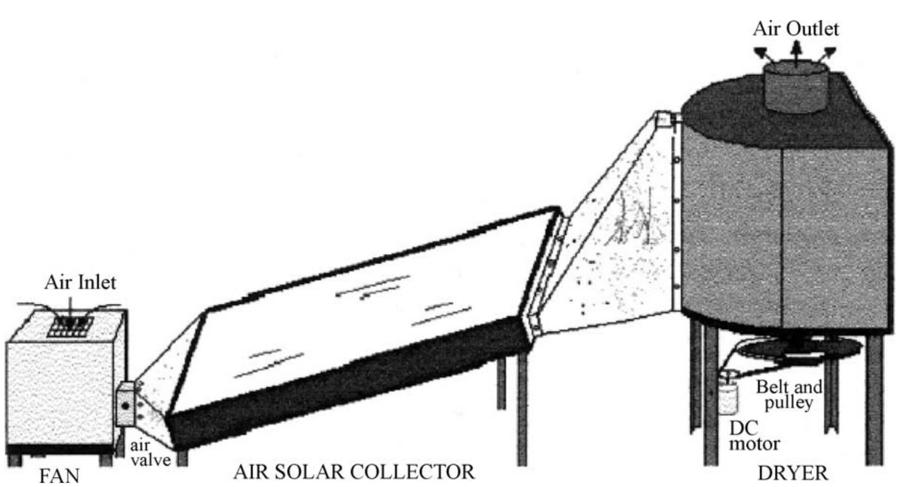


Fig. 37. The complete drying system.

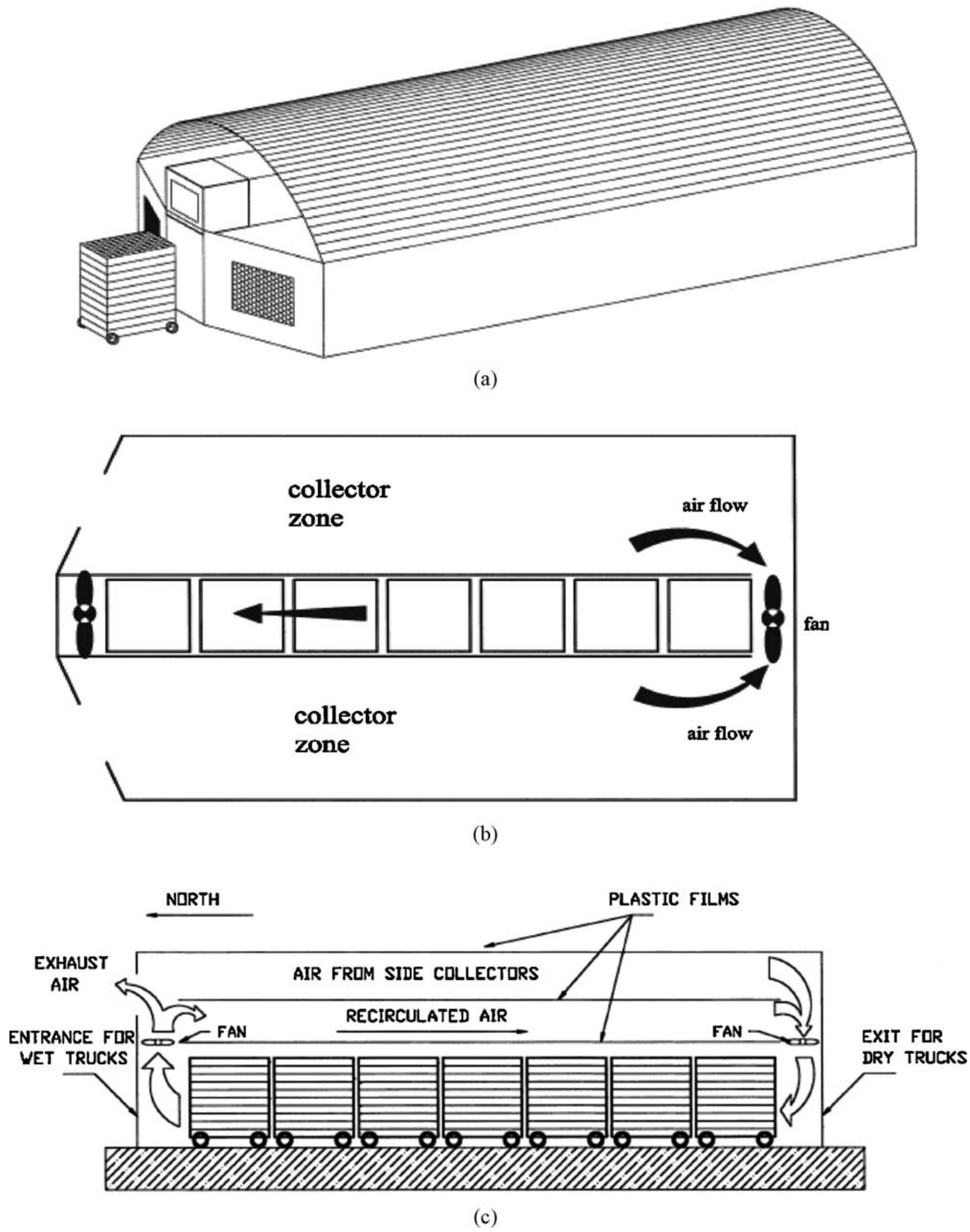


Fig. 38. (a) Face view of the tunnel greenhouse drier. (b) Plant view of the tunnel greenhouse drier. (c) Forced convection greenhouse drier of the tunnel.

in the air inlet, can accelerate the drying rate. The dryer had six perforated trays for loading the material. The absorber plate of the dryer attained a temperature of 97.2 °C when it was studied under no load conditions. The maximum air temperature in the dryer, under this condition was 78.1 °C. The dryer was loaded with 4 kg of bitter gourd having an initial moisture content of 95%, and the final desired moisture content of 5% was achieved within 6 h without losing the product colour, while it was 11 h for open sun drying. The collector glazing was inclined at a particular angle, suitable to the location, for absorption of maximum solar radiation. The quality of the product dried in the solar dryer was competitive with the branded products available in the market.

The effect of air temperature and airflow rate on the drying kinetics of Gelidium Sesquipedale was investigated by the Mohamed et al. [74] in convective solar drying. The drying process was conducted by using an indirect forced convection solar dryer (Fig. 47). It consisted of a solar air collector, an auxiliary heater, a circulation fan and a drying cabinet. Drying was conducted at 40, 50 and 60 °C and thin layer convective solar drying of Gelidium Sesquipedale was investigated. The relative humidity was varied from 50% to 57%, and the drying airflow rate was varied from 0.0277 to 0.0833 m^3/s. The solar Gelidium Sesquipedale drying process occurred in the falling rate period. From the obtained results, it can be concluded that the main factor influencing the drying kinetics was the drying air temperature.

Mohanraj and Chandrasekar [75] designed, fabricated and tested a forced convection solar drier for the drying copra under Indian climatic conditions. A schematic diagram of a forced convection solar drier is shown in Fig. 48. The solar drier consisted of a flat plate solar air heater of area 2 m^2 (2 m × 1 m) connected to a drying chamber. The gap between the glass and the absorber surface was maintained connected to a 0.75 kW (1 HP) centrifugal fan with an airflow rate up to 300 $m^3\ h^{-1}$ and the other side with a drying chamber. A divergent section was provided at the entry of the solar air heater to provide uniform air circulation over the absorber surface. The solar air heater was tilted to an angle about

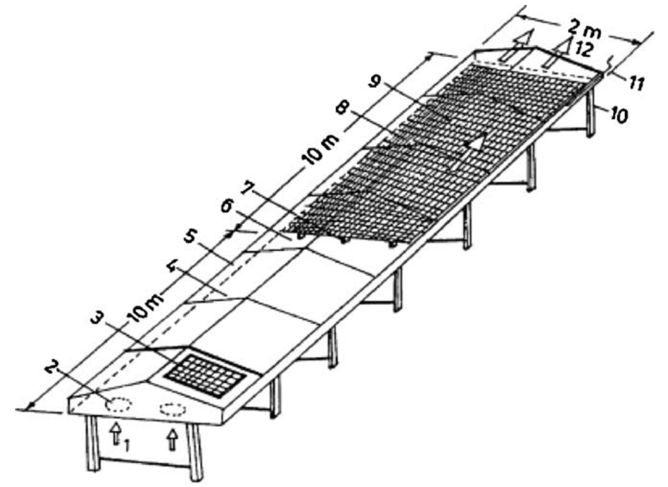


Fig. 39. Solar tunnel drier: (1) air inlet; (2) fan; (3) solar module; (4) solar collector; (5) side metal frame; (6) outlet of the collector; (7) wooden support; (8) plastic net; (9) roof structure for supporting the plastic cover; (10) base structure for supporting the tunnel drier; (11) rolling bar; (12) outlet of the drying tunnel.

Fig. 41. Pictorial view of the experimental set up.

25° with respect to the horizontal, which was considered to be an optimum angle for year-round performance of the system at Pollachi, India. The system was oriented to face the south to maximize the incident solar radiation on the solar collector. On the basis of measurements, Pollachi (latitude of 10.39°N, longitude of 77.03°E), where the experiment was conducted, had about 11 h 30 min of daylight, with typically about 8 h per day of sunshine available for drying. Drying copra in the drier reduced its moisture content from about 51.8% to 7.8% and 9.7% in 82 h for trays at the bottom and top, respectively. The copra obtained was graded as 76% milling grade copra (MCG1), 18% (MCG2) and 6% (MCG3) according to Bureau of Indian Standards (BIS: 6220-1971). The thermal efficiency of the solar drier was estimated to be about 24%.

Janjaia et al. [76] presented experimental performance of solar drying of rosella flower and chilli using roof-integrated solar dryer. Field-level tests for deep bed drying of rosella flower and chilli demonstrated that drying in the roof-integrated solar dryer results in significant reduction in drying time compared to the traditional sun drying method and the dry product is a quality dry product compared to the quality products in the markets. The payback period of the roof-integrated solar dryer is about 5 years. The dryer consists of a roof-integrated solar collector and a drying bin with an electric motor (220 V, 1 phase, 0.373 kW) operated axial flow fan to provide the required airflow (Fig. 49). The bin is connected to the middle of the collector through a T-type air duct. The roof-integrated collector consists of two arrays of collector: one facing the south and other facing the north with a total area of 108 m^2. These arrays of the collectors also serve as the roof of the building. The roof-integrated collector is essentially an insulated black-painted roof serving as an absorber, which is covered with a polycarbonate plate. The building was partitioned into one space for the drying bin and another two additional rooms. The first room was used for the preparation of the product to be dried and the second for the storage of dried products.

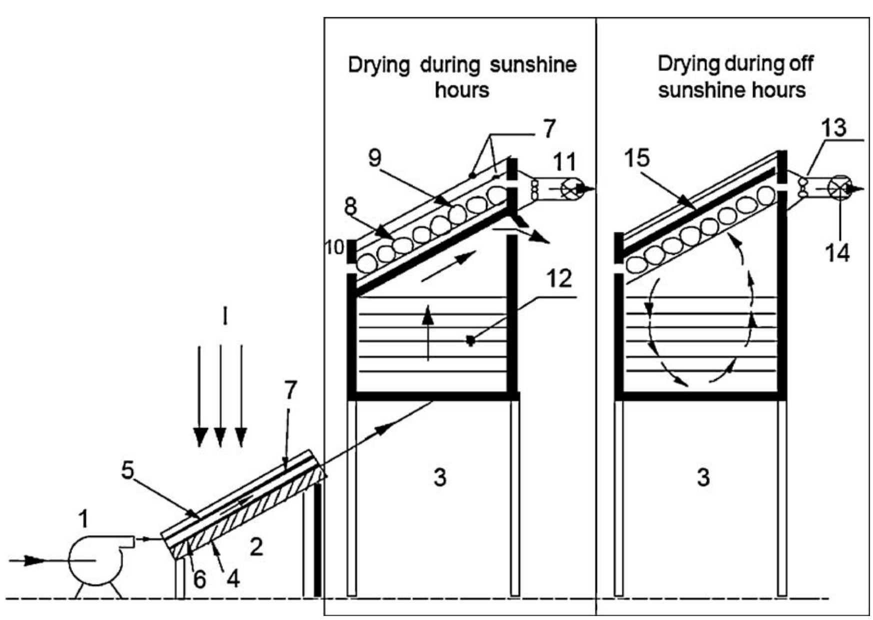


Fig. 40. Schematic view of the desiccant integrated solar dryer.

Fig. 42. Camera photo of the forced flow solar dryer and drying chamber.

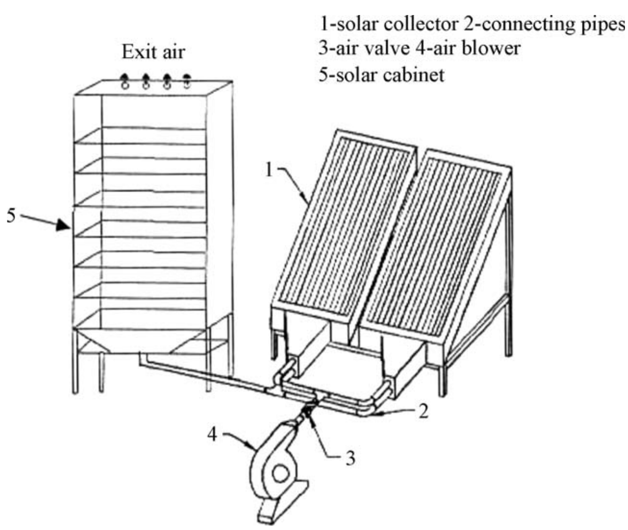


Fig. 43. Illustrate the solar drying.

Smitabhindu et al. [77] developed a drying system consists of two main parts namely: (1) the solar collector, and (2) the drying cabinet (Fig. 50). The solar collector was placed on the rooftop of the drying building and the drying cabinet was inside the building.

Fig. 45. Photograph of solar-assisted forced convection dryer.

The solar collector consists of polyurethane back insulator and cover glass. There was an air gap between the cover glass and the insulator through which ambient air was sucked from both ends of the roofs through the collectors. The air was sucked at the midpoint of the collector and supplied into the drying cabinet with an auxiliary heat source using an LPG gas burner. Each part of the collector was designed with a modular concept. The parts of the collector such as insulation and cover glass were in modular form so that these can be easily transported and connected to each other. The drying cabinet was a tray type and accommodates 15 trays in stacks with a total drying area of 8 m^2 and the dimension of a tray was $1\,m \times 2\,m \times 1.5\,m$. This drying cabinet had been specially designed in such a way that hot air was guided to flow parallel through the products placed in the trays in the stacks. This design had the advantage that air temperatures in the cabinet were uniform. Ambient air preheated by solar collector was sucked by an

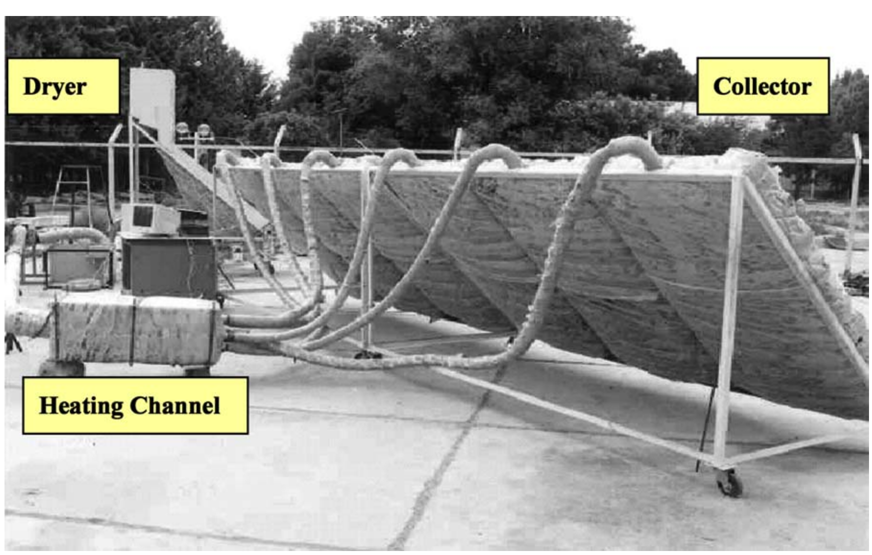


Fig. 44. A new semi-continuous active mixed-mode type drying system (six solar air heaters, heating channel, air ducts, fan and dryer).

Fig. 46. Photograph of the solar dryer.

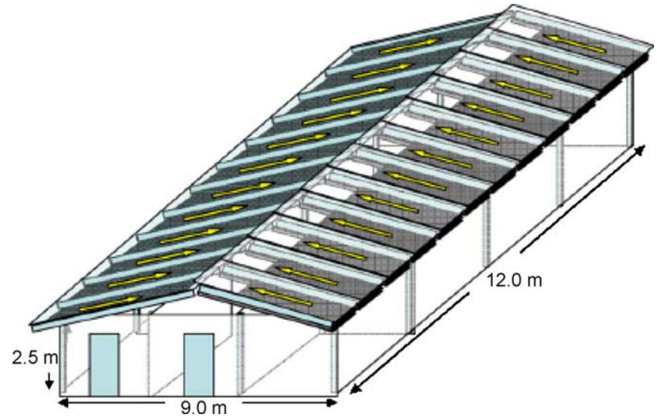


Fig. 49. Roof-integrated solar drying system.

Fig. 47. Photo of laboratory solar dryer.

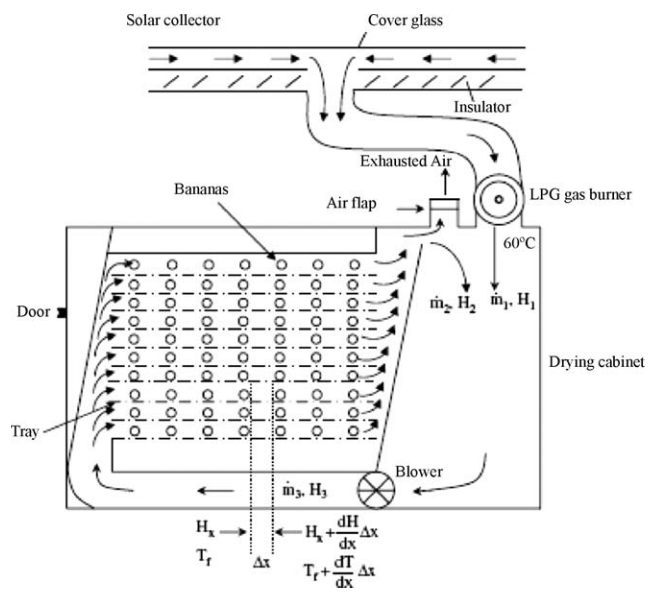


Fig. 50. Schematic diagram of the solar-assisted drying system.

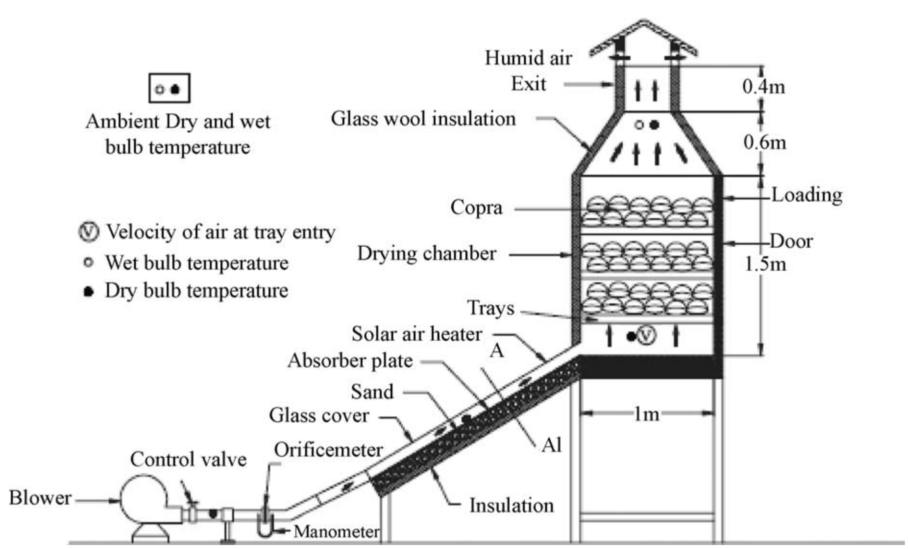


Fig. 48. Schematic view of the solar drier used for copra drying.

Fig. 51. Picture of the drying cabinet inside the building (a) and the solar collector on the roof of the same building (b).

electrical blower and additional heat if needed, was supplied by an LPG gas burner. Then heated air was supplied to the cabinet. The picture of the solar collector and the drying cabinet are shown in Fig. 51.

5. Conclusion

This review paper is focused on the available solar dryer's systems. Authors presented a comprehensive review of the various designs, details of construction and operational principles of the wide variety of practically realized designs of solar-energy drying system. Two broad groups of solar-energy dryers can be identified, viz., passive or natural-circulation solar-energy dryers and active or forced-convection solar-energy dryers. This paper are also present some easy-to-fabricate and easy-to-operate dryers that can be suitably employed at small-scale factories or at rural farming villages. Such low-cost food drying technologies can be readily introduced in rural areas to reduce spoilage, improve product quality and overall processing hygiene. The eventual objective of employing these appropriate drying technologies is to significantly improve the agricultural returns for farmers in appreciation of the hard effort they have devoted in crop cultivation.

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